II

Summary of activities in 2010

1 Theoretical Nuclear Physics Group

Subjects: Structure and reactions of unstable nuclei, Monte Carlo Shell Model, Molecular Orbit Method, Mean Field Calculations, Quantum Chaos
Quark-Gluon Plasma, Lattice QCD simulations, Structure of Hadrons, Color superconductivity
Relativistic Heavy Ion Collisions, Relativistic Hydrodynamics, Color Glass Condensate

Member: Takaharu Otsuka, Tetsuo Hatsuda, Tetsufumi Hirano, Noritaka Shimizu and Shoichi Sasaki

In the nuclear theory group, a wide variety of subjects are studied. The subjects are divided into three major categories: Nuclear Structure Physics, Quantum Hadron Physics and High Energy Hadron Physics.

Nuclear Structure Physics

In the Nuclear Structure group (T. Otsuka and N. Shimizu), quantum many-body problems for atomic nuclei, issues on nuclear forces and their combinations are studied theoretically from many angles. The subjects studied include (i) structure of unstable exotic nuclei, (ii) shell model calculations including Monte Carlo Shell Model, (iii) collective properties and IBM, (iv) reactions between heavy nuclei, (v) other topics such as Bose-Einstein condensation, quantum chaos, etc.

The structure of unstable nuclei is the major focus of our interests, with current intense interest on novel relations between the evolution of nuclear shell structure and characteristic features of nuclear forces, for example, tensor force, three-body force, etc. Phenomena due to this evolution includes the disappearance of conventional magic numbers and appearance of new ones. We have published pioneering papers on the shell evoltion in recent years. The tensor force effect has been clarified in [1], while striking effect of three-body force has been shown in [2] for the first time. The structure of such unstable nuclei have been calculated by Monte Carlo Shell Model and conventional shell model with further developments, for example, a new extrapolation method [3]. Their applications have been made in collaborations with experimentalists in internationally distributed, *e.g.*, [4, 5].

The mean-field based formulation of the Interacting Boson Model is a new original approach being developed [6]. This approach is so general and powerful that its applications are being spread very fast in big collaborations [7].

We are studying on time-dependent phenomena like fusion and multi-nucleon transfer reactions in heavy-ion collisions. A new insight on the role of fast charge equilibration at the initial stage of the reaction has been presented [8].

Quantum Hadron Physics

In Quantum Hadron Physics group (T. Hatsuda and S. Sasaki), many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). Main research interests are the quark-gluon structure of hadrons, lattice gauge theories and simulations, matter under extreme conditions, quark-gluon plasma in relativistic heavy-ion collisions, high density matter, neutron stars and quark stars, chiral symmetry in nuclei, color superconductivity, and many-body problem in cold atoms and in graphene. Highlights in research activities of this year are listed below:
1. Lattice QCD studies on hadron interaction [9]
2. Lattice QCD studies on baryon-baryon potential [10]
3. Random matrix theory for high density matter [11]
4. Boson-fermion mixture in ultracold atoms [12]
5. Gap formation in monolayler graphene [13]
6. Resummation of perturbation theory [14]

High Energy Hadron Physics

In High Energy Hadron Physics group (T. Hirano), the physics of the quark-gluon plasma and dynamics of relativistic heavy ion collisions are studied theoretically based on relativistic hydrodynamics and relativistic kinetic theories. Main subjects include (1) hydrodynamic description of the space-time evolution of the quark-gluon plasma in relativistic heavy ion collisions [15, 16, 18], (2) transport description of hadrons and their dissipation (3) analyses of the quark-gluon plasma through hard probes such as jets and heavy quarks/quarkonia , (4) color glass condensate for high energy colliding hadrons/nuclei, and (5) quantum non-abelian votex in dense QCD matter [17]

References

[1] Takaharu Otsuka, Toshio Suzuki, Michio Honma, Yutaka Utsuno, Naofumi Tsunoda, Koshiroh Tsukiyama, and Morten Hjorth-Jensen, "Novel Features of Nuclear Force and Shell Evolution in Exotic Nuclei", Phys. Rev. Lett.,**104**, 012501 (2010) (Selected for a Viewpoint in *Physics*)

[2] T. Otsuka, T. Suzuki, J.D. Holt, *et al.*, "Three-Body Forces and the Limit of Oxygen Isotopes", Phys. Rev. Lett., **105**, 032501 (2010)

[3] N. Shimizu, Y. Utsuno, T. Mizusaki, T. Otsuka, T. Abe, M. Honma, "Novel extrapolation method in the Monte Carlo shell model", Phys. Rev., **C82**, 061305 (2010)

[4] P. Fallon, E. Rodriguez-Vieitez, A.O. Macchiavelli, *et al.*, "Two-proton knockout from Mg-32: Intruder amplitudes in Ne-30 and implications for the binding of F-29, F-31", Phys. Rev., **C81**, 041302 (2010).

[5] A.N. Deacon, J.F. Smith, S.J. Freeman, *et al.*, "Cross-shell excitations near the "island of inversion": Structure of Mg-30", Phys. Rev., **C82**, 034305 (2010)

[6] K. Nomura, N. Shimizu, T. Otsuka, "Formulating the interacting boson model by mean-field methods", Phys. Rev., **C81**, 044307 (2010)

[7] K. Nomura, T. Otsuka, R. Rodriguez-Guzman, *et al.*, "Structural evolution in Pt isotopes with the interacting boson model Hamiltonian derived from the Gogny energy density functional", Phys. Rev., **C83**, 014309 (2011)

[8] Y. Iwata, T. Otsuka, J.A. Maruhn, *et al.*, "Suppression of Charge Equilibration Leading to the Synthesis of Exotic Nuclei", Phys. Rev. Lett., **104**, 252501 (2010)

[9] T. Kawanai and S. Sasaki, "Charmonium-nucleon potential from lattice QCD", Phys. Rev. **D82**, 091501(R) (2010).

[10] T. Inoue, N. Ishii, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, K. Murano, H. Nemura, K. Sasaki [HAL QCD collaboration], "Baryon-baryon interactions in the flavor SU(3) limit from full QCD simulations on the lattice", Prog. Theor. Phys. **124**, 591 (2010).

[11] G. Akemann, T. Kanazawa, M.J. Phillips, T. Wettig, "Random matrix theory of unquenched two-colour QCD with nonzero chemical potential", JHEP **1103**, 066 (2011)

[12] Kenji Maeda, "Large N expansion for Stronglycoupled Boson-Fermion Mixtures", Ann. Phys. **326**, 1032-1052 (2011).

[13] Y. Araki, "Chiral Symmetry Breaking in Monolayer Graphene by Strong Coupling Expansion of Compact and Non-compact U(1) Lattice Gauge Theories", Ann. Phys. (2011) in press.

[14] T. Hayata, "Rescaled Perturbation Theory", Prog. Theor. Phys. **124**, 1097 (2010).

[15] A. Monnai and T. Hirano: "Relativistic Dissipative Hydrodynamic Equations at the Second Order for Multi-Component Systems with Multiple Conserved Currents", Nucl. Phys. A **847**, 283 (2010).

[16] T. Hirano, P. Huovinen and Y. Nara: "Elliptic flow in U+U collisions at $\sqrt{s_{NN}} = 200$ GeV and in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV: Prediction from a hybrid approach", Phys. Rev. C **83**, 021902(R) (2011).

[17] Y. Hirono, T. Kanazawa and M. Nitta: "Topological Interactions of Non-Abelian Vortices with Quasi-Particles in High Density QCD", to appear in Phys. Rev. **D** (arXiv:1012.6042[hep-ph]).

[18] H. Song, S. A. Bass, U. W. Heinz, T. Hirano and C. Shen: "200 A GeV Au+Au collisions serve a nearly perfect quark-gluon liquid", to appear in Phys. Rev. Lett. (arXiv:1011.2783 [nucl-th]).

2 Theoretical Particle and High Energy Physics Group

Research Subjects: The Unification of Elementary Particles & Fundamental Interactions

Members: Takeo Moroi, Tsutomu Yanagida, Koichi Hamaguchi, Yutaka Matsuo

The main research interests at our group are in string theory, quantum field theory and unification theories. String theory, supersymmetric field theories, and conformal field theories are analyzed relating to the fundamental problems of interactions. In the field of high energy phenomenology, supersymmetric unified theories are extensively studied and cosmological problems are also investigated.

We list the main subjects of our researches below.

1. High Energy Phenomenology.
   - 1.1 LHC Phenomenology [2] [19] [14] [16]
   - 1.2 Dark Matter [15] [1] [4]
   - 1.3 Supersymmetric models [6] [17] [3]
   - 1.4 B meson mixing [5] [21]
   - 1.5 Anomaly puzzle [7]
   - 1.6 Inflation Model [18]
   - 1.7 Holographic QCD
   - 1.8 Chiral fermion on the lattice [8] [9]
2. Superstring Theory.
   - 2.1 F theory [12] [13]
   - 2.2 Correspondence between 4D supersymmetric gauge theory and 2D gravity [10]
   - 2.3 AdS/CFT Correspondence, Kerr/CFT Correspondence [20]

References

[1] K. Ishiwata, S. Matsumoto and T. Moroi, “Decaying Dark Matter in Supersymmetric Model and Cosmic-Ray Observations,” JHEP **1012**, 006 (2010).

[2] T. Ito and T. Moroi, “Spin and Chirality Determination of Superparticles with Long-Lived Stau at the LHC,” Phys. Lett. B **694**, 349 (2011).

[3] S. K. Kang, T. Morozumi and N. Yokozaki, “Effects of Large Threshold Corrections in Supersymmetric Type-I Seesaw Model,” JHEP **1011**, 061 (2010) [arXiv:1005.1354 [hep-ph]].

[4] K. Hamaguchi and N. Yokozaki, “Soft Leptogenesis and Gravitino Dark Matter in Gauge Mediation,” Phys. Lett. B **694**, 398 (2011) [arXiv:1007.3323 [hep-ph]].

[5] M. Endo and N. Yokozaki, “Large CP Violation in B_s Meson Mixing with EDM constraint in Supersymmetry,” JHEP **1103**, 130 (2011) [arXiv:1012.5501 [hep-ph]].

[6] T. T. Yanagida, K. Yonekura, “A Conformal Gauge Mediation and Dark Matter with Only One Parameter,” Phys. Lett. **B693**, 281-286 (2010). [arXiv:1006.2271 [hep-ph]].

[7] K. Yonekura, “Notes on Operator Equations of Supercurrent Multiplets and Anomaly Puzzle in Supersymmetric Field Theories,” JHEP **1009**, 049 (2010). [arXiv:1004.1296 [hep-th]].

[8] Y. Kikukawa and K. Usui, “Reflection Positivity of Free Overlap Fermions,” Phys. Rev. D **82**, 114503 (2010) [arXiv:1005.3751 [hep-lat]].

[9] Y. Kikukawa and K. Usui, “Reflection Positivity of N=1 Wess-Zumino model on the lattice with exact $U(1)_R$ symmetry,” arXiv:1012.5601 [hep-lat].

[10] S. Kanno, Y. Matsuo and S. Shiba, "Analysis of correlation functions in Toda theory and AGT-W relation for SU(3) quiver," Phys. Rev. D **82**, 066009 (2010) [arXiv:1007.0601 [hep-th]].

[11] T. Kawano and F. Yagi, "a-Maximization in $\mathcal{N} = 1$ Supersymmetric $Spin(10)$ Gauge Theories," Int. J. Mod. Phys. A **25**, 5595 (2010).

[12] H. Hayashi, T. Kawano, Y. Tsuchiya and T. Watari, "Flavor Structure in F-theory Compactifications," JHEP **1008**, 036 (2010).

[13] H. Hayashi, T. Kawano, Y. Tsuchiya, T. Watari, "More on Dimension-4 Proton Decay Problem in F-theory -Spectral Surface, Discriminant Locus and Monodromy-," Nucl. Phys. **B840**, 304-348 (2010).

[14] R. Sato, S. Shirai, "LHC Reach of Low Scale Gauge Mediation with Perturbatively Stable Vacuum," Phys.Lett.B692:126-129, 2010.

[15] R. Saito, S. Shirai, "Primordial Black Hole as a Source of the Boost Factor," Phys.Lett.B697:95-100,2010.

[16] E. Nakamura, S. Shirai, "Discovery Potential for Low-Scale Gauge Mediation at Early LHC," JHEP 1103:115, 2011.

[17] M. Ibe, R. Sato, T. T. Yanagida and K. Yonekura, "Gravitino Dark Matter and Light Gluino in an R-invariant Low Scale Gauge Mediation," arXiv:1012.5466 [hep-ph].

[18] N. Haba, S. Matsumoto and R. Sato, "Sneutrino Inflation with Asymmetric Dark Matter," arXiv:1101.5679 [hep-ph].

[19] M. Endo, K. Hamaguchi, K. Nakaji, "Probing High Reheating Temperature Scenarios at the LHC with Long-Lived Staus," JHEP **1011**, 004 (2010). [arXiv:1008.2307 [hep-ph]].

[20] T. Nishioka, H. Tanaka, "Lifshitz-like Janus Solutions," JHEP 02 (2011) 023

[21] M. Endo, S. Shirai and T. T. Yanagida, "Split Generation in the SUSY Mass Spectrum and $B_s - \bar{B}_s$ Mixing," to appear in PTP. [arXiv:1009.3366 [hep-ph]].

3 Hayano Group

Research Subjects: Precision spectroscopy of exotic atoms and nuclei

Member: Ryugo S. Hayano and Takatoshi Suzuki

1) Antimatter study at CERN's antiproton decelerator

Antiprotonic helium laser spectroscopy Atomic transition frequencies in antiprotonic helium (together with those in hydrogen) yield information on the Rydberg constant and the proton-to-electron mass ratio, thereby contributing to the CODATA 2006 recommended values of the fundamental physical constants.

In order to further improve the antiprotonic helium laser spectroscopy precision, we have developed new Doppler-free spectroscopy methods with which it should be possible to determine the (anti)proton-to-electron mass ratio with a relative standard uncertainty better than 10^{-10} (i.e., better than the current CODATA value) within a few years.

Antihydrogen Spectroscopic comparison of hydrogen and antihydrogen ($\bar{p} - e^+$) atoms is considered to be one of the most stringent test of the CPT symmetry. At CERN, we can now routinely form antihydrogen atoms by mixing antiprotons and positrons, and our current goal is to capture antihydrogen atoms by using a superconducting octupole magnet system. At the same time, development of an "antihydrogen beam", with which we plan to measure the antihydrogen ground-state hyperfine splitting, is in progress.

$\bar{p}$-nucleus annihilation cross section at ultra-low energies At high energies, it is known that the $\bar{p}$-nucleus annihilation cross sections scale as $\sigma_{\text{ann}} \propto A^{2/3}$ where A is the nuclear mass number. However, at very low energies, this scaling is expected to be violated, but no such measurements have been done due to the lack of ultra-low-energy antiproton beams. Using a radio-frequency quadrupole decelerator ("inverse" linac), we have started the σ_{ann} measurements at 100 keV. In 2010, we developed a beam profile monitor for the ultra-low-energy antiproton beams, and succeeded in precisely guiding the beams to our targets using this monitor and ion-optical calculations. We are now developing detectors to measure the cross sections, and we will carry the measurement of the $\bar{p}$-nucleus annihilation cross sections.

2)Laser spectroscopy of radioactive francium isotopes at the ISOLDE facility at CERN

Laser spectroscopy is a crucial tool for studying properties of nuclear ground states. At the ISODLE facility at CERN, the new CRIS collaboration of Manchester, Leuven, Birmingham, Orsay, Max Planck Institute of Quantum Optics, and Tokyo has proposed to measure the isotope shifts and hyperfine structures of francium isotopes by collinear resonant ionization spectroscopy (CRIS). The CRIS method may provide evidence of the anomalous structure in neutron deficient francium isotopes.

For the CRIS method, we plan to use a nanosecond titanium-sapphire laser developed by the ASACUSA experiment at CERN. This laser will be operated with a high output power of ∼kW and a narrow linewidth of 100 MHz, and thus allow the measurement of the isotope shifts (∼10 GHz) and hyperfine structures (∼100 MHz) of francium isotopes with relatively low yields (several ions/s). In 2010, we have started to set up the laser for the experiment in 2011.

3) Precision X-ray spectroscopy of kaonic atoms

The X-ray spectroscopy of kaonic atoms is a complementary tool to study kaon-nucleon/nucleus interaction. The advent of a new type of high-resolution x-ray detector, SDD, its combination with high-intensity beamline provides clean kaon beam and various trackers/counters technique, enables us to study kaonic atoms with unprecedented precision.

X-ray spectroscopy of kaonic atoms at DAΦNE In fiscal year 2010, we analyzed the data of hydrogen and helium-3 target measurement carried out during the beam time of SIDDHARTA experiment in fiscal year 2009. For kaonic hydrogen atom, we are finalizing the conclusion on its 1s-level shift and width with respect to the energy level determined only by the electromagnetic interaction. The result will be published in the coming months. On the other hand, from the first measurement of kaonic helium-3 X-ray in SIDDHARTA experiment, we determined with a precision of less than 10 eV that the 2p-level shift of kaonic helium-3 atom is a small one close to zero. To establish a concrete conclusion on the 2p-level shift of kaonic helium-3 atom, the result from E17 experiment under preparation at J-PARC is necessary.

X-ray spectroscopy of kaonic helium at J-PARC The 2p-level shifts in kaonic helium 3 and kaonic helium 4, and the isotopic shift between them give a strong constraint to the kaon-nucleas interaction. A recent x-ray measurement by SIDDHARTA group implied a finite isotopic shift which can not be explained by the optical model framework. Then, the J-PARC E17, which is the first experiment to be carried out at K1.8BR beamline in the J-PARC hadron experimental facility, is now proposing kaonic helium 4 measurement, in addition to the originally proposed kaonic helium 3 measurement, to precisely determine the isotopic shift. In fiscal year 2010, we proceeded the kaon beam tuning of K1.8BR beamline and succeeded in operating SDDs (silicon drift x-ray detectors) under the beam condition . The damage to our detectors by the earthquake is limited and the E17 is expected to run soon after the recovery of the facility.

4) Study of kaonic nuclei

Study of kaonic nucleus via the stopped K^- reaction on helium 4 In FSY 2005, we have performed KEK-PS E549, to measure (semi-)inclusive ^{4}He($K^-_{stopped}, N$) spectra, and obtained strict upper limits for the formation of narrow $\bar{K}NNN$ states with total isospin $T = 0/1$. Meanwhile, the ^{4}He($K^-_{stopped}, YN/Yd$) semi-exclusive spectra exhibitted unresolved wide strengths which are well separable from multi-nucleon processes. They could be the signal of non-mesonic YN/YNN decay of strongly-bound $\bar{K}NN/\bar{K}NNN$ states. In FSY 2010, we have further identified $\Sigma^0 NNN$ final states by the study of ΛNN triple coincidence events, and found that the proton momentum spectrum from the final states is clearly deviated from the one expected from the two-nucleon absorption process, and most likely to be the signal of those multibaryonic states. As a byproduct, we have identified the four-nucleon absorption process of K^- meson at rest, $K^{-4}\mathrm{He} \to \Lambda t$ for the first time.

Search for K^-pp and K^-pn deeply-bound kaonic states at J-PARC The J-PARC E15, to be scheduled after E17 at K1.8BR beamline, will use the $^3\mathrm{He}(K^-, N)$ reaction to search for K^-pp/K^-pn. E15 is a kinematically complete experiment in which all reaction products are detected exclusively especially for $K^-pp \to \Lambda p$ channel, and it aims to provide decisive information on the nature of the simplest kaonic nucleus. In FSY 2010, we have installed the Cylindrical Drift Chamber (CDC) into the solenoid magnet, tested the performance of the system (Cylindrical Detector System - CDS) with the activated magnetic field, and performed the CDS calibration with 0.9 GeV/c K^- beam, so that $\Lambda \to p\pi^-$ and $K^0_s \to \pi^+\pi^-$ reactions were successfully reconstructed.

5) Precision spectroscopy of pionic atoms

We are planning a precise pionic-atom spectroscopy experiment with BigRIPS at RIBF. The goal is to study 1s and 2s pionic states in ^{121}Sn by the $^{122}\mathrm{Sn}(d,^3\mathrm{He})$ reaction. The measurement will help us better understand the strong interaction between the pion and the nucleus, which leads to quantitative evaluation of the magnitude of the quark condensate at the normal nuclear density.

In October 2010 we performed a pilot experiment to construct ion optics for the dispersion matching with the $(d,^3\mathrm{He})$ reaction and to check performance of the focal plane detectors which will be used in the production experiment. The beam was provided by the SRC with an energy of 250 MeV/nucleon and an intensity of $\sim 4 \times 10^{11}$/s. This high intensity deuteron beam hits the target, 10 mg/cm^2 ^{122}Sn, and produces a large number of protons of $\sim$ 200 kHz as background at the focal plane.

We could construct the BigRIPS optics by using the ^{14}N beam and the thick Cu target and confirm the optics of the beam transfer line was consistent with the designed optics. We also confirmed that all detectors worked with high intensity beam as we expected. We could measure the track with the design resolution by MWDCs and identify ^{3}He in the large background of protons by TOF and energy loss of scintillators.

6) Study of muonium production targets

Ultra-slow polarized muon beam whose energy of 0.5∼30keV is anticipated as a new "microscope for magnetism" for the investigation of the surface magnetism. The ultra slow muon beamline was established in the RIKEN RAL muon facility. In this site, 15∼20/s ultra-slow muons can be generated while initial muon beam intensity reaches to 1.3 $\times 10^6$ /s. In order to increase the intensity of the ultra-slow muons, improvements of the escaping efficiency of the muonium from the muonium formation target (3%), and laser ionization ($\sim 10^-5$) are needed. As for muonium formation target, silica-based or alumina-based materials are promising. In order to develop the new muonium formation target, we fabricated samples of (i)Silica nanoporous plate(ii)Alumina nanoporous plate (iii)Silica Aerogel, and measured muon-muonium conversion rate and muonium diffusion of them in TRIUMF. As a result, sample(iii) has muon-muonium conversion rate of 70% compared to heat-tungsten foil(T= 3000 K) that have been used in RIKEN RAL facility. Meanwhile, energy of emitted muonium is comparable with thermal energy of room temperature so that the density distribution of muonium around the target surface suppose to be higher than that of conventional muonium target. In the next year, with a new laser system, we will perform practical test of new muonium production target in the RIKEN-RAL muon facility.

4 Ozawa Group

Research Subjects: Experimental study of non-perturbative QCD

Member: Kyoichiro Ozawa

Study of quark-gluon-plasma at RHIC

In 10 years operation of Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), many new phenomena related to hot and dense nuclear matter have been discovered. We performed the PHENIX experiment at RHIC and produced many new results on a wide range of physics subjects, including charged and neutral hadron production, single electron production, event isotropy, and many other topics.

In spite of these fruitful results, there are still remaining questions to be answered to further characterize the state of matter formed at RHIC. In particular, chiral properties of the dense matter produced has not been obtained, and should be provided. For the study of the chiral properties, vector mesons, such as ϕ, ω and ρ are interesting mesons because the restoration of approximate chiral symmetry at high temperature may modify their mass and width. These modifications can be shown directly in the line shape of the e^+e^- mass spectra. Here, the measurements with lepton decays are essential, since leptons are not interact with the medium and carry direct information about conditions and properties of the medium. However, large background in electron pairs due to π^0 Dalitz decays and γ conversion make the measurement difficult in the past RHIC data. In the last year, we have successfully installed and operated a new detector, which is called Hadron Blind Detector(HBD), to suppress the background.

In this year, we have focused on rejection of gamma conversions at HBD itself, since such conversions can be a serious background in high multiplicity environment due to a scintillation light. As a result, we have successfully developed analysis scheme to reject such background statistically.

Study of mechanism of hadronic mass generation at J-PARC

The chiral property of QCD in dense($\rho \neq 0$) nuclear matter has also attracted wide interest in the field of hadron physics. In hot and/or dense matter, broken chirtal symmetry is subject to be restored either partially or completely and, hence, the properties of hadrons can be modified. To observe such an effect, measurements of the in-medium decay of vector mesons are highly desirable for the direct determination of the meson properties in matter. We are planning two new experiments at J-PARC to measure vector meson mass at normal nuclear density.

One new experiment aim to collect 100 times larger statistics of ϕ meson than that collected by the KEK experiment. We can discuss the velocity dependence of the mass spectra of vector mesons more precisely and compare with the theoretical predictions. We are also able to use larger and smaller nuclear targets as lead and proton, For this experiment, new detector based on Gas Electron Multiplier (GEM), which is originally developed at CERN, is under developing. Using GEM, we are investigating 2 dimensional tracker for high rate counting. A prototype is reconstructed and reasonable signals are observed.

In this year, large sizes (20cm and 30cm) of GEM foils are developed and tested. An test experiment is performed at LNS test beam line at Tohoku Univ. Position resolutions of large size GEMs are evaluated using an electron beam. As shown in Fig. 2.1.5, a position resolution of 100 μm is obtained both for 20 cm and 30 cm GEMs.

Also, we propose combined measurements of nuclear ω bound state and direct ω mass modification. Nuclear ω bound states are measured in p(π^-, n)ω reaction and decays of generated ω meson are also measured with $\omega \to \pi^0\gamma$ mode. Such exclusive measurement can supply essential information to establish partial restoration of the chiral symmetry in nucleus.

We constructed TOF counters in this year and tested them at LEPS beam line at Spring-8 to evaluate its timing resolution and neutron efficiency. The timing resolution of 60 ps is obtained. Analysis for the neutron efficiency is on-going.

Tests of EM Calorimeter is performed at LNS GeV-γ beam line at Tohoku University. As a EM Calorimeter, we are planning to use CsI crystals, which is used at KEK-E246. Photon readout on CsI crystal is changed from Photo Diode to Avalanche photo diode to cope with high counting rate at J-PARC. Then, energy resolution of CsI crystal and Avalanche photo diode is evaluated using an electron beam. Results are shown in Fig. 2.1.6. Obtained energy resolution is enough for our purpose.

5 Komamiya group

Research Subjects: (1) Preparation for an accelerator technology and an experiment for the International linear e^+e^- collider ILC; (2) Experiment for studying gravitational quantum effects and searching for new medium range force using ultra-cold neutron beam; (3) Physics analyses in the ATLAS experiment at the LHC *pp* collider; (4) Data analyses for the BES-II experiment at BEPC-I, and TOF detector construction for BES-III experiment at BEPC-II;

Member: Sachio Komamiya, Yoshio Kamiya

We, particle physicists, are entering an exciting period in which new paradigm of the field will be opened on the TeV energy scale by new discoveries expected in experiments at high-energy frontier colliders, LHC and ILC.

1) Preparation for the International e^+e^- Linear Collider ILC: ILC is the energy frontier machine for e^+e^- collisions in the near future. In 2004 August the main linac technology was internationally agreed to use superconducting accelerator structures. In 2007 March, the Reference Design Report was issued by the Global Design Effort (GDE) and hence the project has been accelerated as an international big-science project. The technical design will be completed in the end of 2012. We are working on ILC accelerator related hardware development, especially on the beam delivery system. We are developing the Shintake beam size monitor for the ATF2, which is a test accelerator system for ILC located at KEK. The Shintake beam size monitor is able to measure O(10)[nm] beam size, by using a high power laser interferometer. The electron beam is emitted to the interference fringe of the split laser beams. The total energy of photons, which are emitted from the inversed Compton scattering of beam electrons with the laser beam interference fringe, is measured by a multilayer CsI(Tl) detector in the down stream. The phase of the fringe is moved step-by-step, the total photon energy is measured in each step, and the beam size is extracted from a fitting of modulation pattern of the total photon energy as a function of the phase. Also we have been studying possible physics scenario and the large detector concept (ILD) for an experiment at ILC.

2) Experiment for studying quantum bound states due to the earth's gravitational potential and searching for new short-range force using ultra-cold neutron beam: A detector to measure gravitational bound states of ultra-cold neutrons is developed. We decided to use CCD's for the position measurement of the UCN's. The CCD is going to be covered by a ^{10}B layer to convert neutron to charged nuclear fragments. The UCNs are going through a neutron guide of 100 [μ] height and their density is modulated in height as forming bound states within the guide due to the earth's gravity. In 2008 we tested our neutron detector at ILL Grenoble. In 2009 we started the test experiment at ILL. We are analyzing the data. We will improve our detector and measure the modulation of the neutron density distribution in 2011.

3) ATLAS experiment at LHC: The epoch of new paradigm for particle physics is going to open with the experiments at LHC. LHC started its operation in the end of 2009. The high energy collision at 7 TeV (CMS) has been started in the end of March 2010. The ATLAS detector is continuously recording data at high energies. Some of our students work on data analysis at LHC. Search for supersymmetric particles with the missing transverse energy and with b-quark signal.

4) BES-II/-III experiment at IHEP: The group has considered the BES-III experiment at the Beijing e^+e^- collider BEPC-II as the candidate for the middle term project before ILC. We have made a research and development for TOF detector for the BES-III experiment together with IHEP, USTC. We successfully completed a test of over 500 photomultipliers in 1[T] magnetic field and they are already installed to the BES-II detector. We have studied the data analysis of baryon-pair production in $J\psi$ decay using 5.8M BES-II J/ψ events. Now BEPC-II is operating smoothly and BES-III detector is taking large samples of ψ' and J/ψ data.

6 Minowa-Group

Research Subjects: Experimental Particle Physics without Accelerators

Member: MINOWA, Makoto and INOUE, Yoshizumi

Various kinds of astro-/non-accelerator/low-energy particle physics experiments have been performed and are newly being planned in our research group.

We started a new R and D study of a compact mobile anti-electron neutrino detector with plastic scintillators to be used at a nuclear reactor station, for the purpose of monitoring the power and plutonium content of the nuclear fuel. It can be used to monitor a reactor from outside of the reactor containment with no disruption of day-to-day operations at the reactor site. This unique capability may be of interest for the reactor safeguard program of the International Atomic Energy Agency(IAEA). We have built a prototype detetctor of a size of $1700 \times 667 \times 551$ mm^3 and weight of 270kg. It is now deployed at Hamaoka Nuclear Power Station of Chube Electric Power Co., Inc.

We are running an experiment to search for axions, light neutral pseudoscalar particles yet to be discovered. Its existence is implied to solve the so-called strong CP problem. The axion would be produced in the solar core through the Primakoff effect. It can be converted back to an x-ray in a strong magnetic field in the laboratory by the inverse process. We search for such x-rays coming from the direction of the sun with the TOKYO AXION HELIOSCOPE, aka Sumico. Sumico consists of a cryogen-free 4 T superconducting magnet with an effective length of 2300 mm and PIN photodiodes as x-ray detectors. By now, we put upper limits of $g_{a\gamma\gamma} < (5.6\text{–}13.4) \times 10^{-10}\text{GeV}^{-1}$ to axion - photon coupling constant for the axion mass $m_a < 0.27$ eV and $0.84 \text{ eV} < \mathrm{m_a} < 1.00$ eV. The latter is a newly explored mass region which CERN Axion Solar Telescope(CAST) group that started later has not reached yet. We planned to continue the measurement in which we scan the mass region from 1 eV upward.

An experiment is being performed for a search for hidden sector photons kinetically mixing with the ordinary photons. The existence of the hidden sector photons and other hidden sector particles is predicted by extensions of the Standard Model, notably the ones based on string theory. The hidden sector photon is expected to come from the direction of the sun. It would be produced in the solar core or in the space by oscillation of the ordinary photon, and can transmute into the photon again in a long vacuum chamber in the laboratory. A photon sensor in the chamber would readily detects the ordinary photon. The detector is now ready and piggybacked onto the Sumico helioscope. We let the detector track the sun to search for the hidden sector photons coming from the sun and found no significant signal for the hidden sector photon. We put upper limits to the mixing angle χ of the normal photon and the hidden sector photon in the unexplored parameter region around the hidden sector photon mass region around a few millielectron volts. This is the world's first solar hidden sector photon search experiment with a dedicated solar hidden sector photon telescope.

7 Aihara/Yokoama Group

Research Subjects: Study of CP-Violation and Search for Physics Beyond the Standard Model in the B Meson and the τ Lepton Systems (Belle & Belle II), Dark Energy Survey at Subaru Telescope (Hyper Suprime-cam), Long Baseline Neutrino Oscillation Experiment (T2K), R&D for the Next Generation Neutrino and Nucleon Decay Experiment (Hyper-Kamiokande), Measurement of Neutrino-nucleus Interactions (SciBooNE), and R&D for Hybrid Photodetectors.

Staff Members: H. Aihara, M. Yokoyama, H. Kakuno and T. Abe

One of the major research activities in our group has been a study of CP-violation and a search for physics beyond the Standard Model in the B meson and the τ lepton systems using the KEK B-factory (KEKB). This past year, we began a study of anomalous magnetic moment of the τ lepton, $(g-2)_\tau$, which is sensitive to physics beyond the Standard Model. Using $\sim$ 900 million τ-$\bar{\tau}$ pairs recorded with the Belle detector, we intend to improve a precision of $(g-2)_\tau$ measurement by a factor of $\sim$ 10 over previous measurements.

The Super KEKB project started in 2010. The upgraded accelerator, Super KEKB, will have 40 times more luminosity than KEKB. The Belle detector is also being upgraded as Belle II detector with cutting-edge technology. One of key elements for the success of Belle II will be the reduction and control of the background from accelerator. We measured the background level of KEKB with a special run. By extrapolating it to the Super KEKB condition with a simulation, we estimated the background level at Belle II. The optimization of interaction region is in progress based on our results.

As an observational cosmology project, we are involved in building a 1.2 Giga pixel CCD camera (Hyper Suprime-Cam) to be mounted on the prime focus of the Subaru telescope. With this wide-field camera, we plan to conduct extensive wide-filed deep survey to investigate weak lensing. This data will be used to develop 3-D mass mapping of the universe. It, in turn, will be used to study Dark Energy.

The T2K long baseline neutrino oscillation experiment started in April 2009. We have searched for $\nu_\mu \to \nu_e$ oscillation using data collected from January to June 2010. One candidate of electron neutrino event is observed at the Super-Kamiokande detector, while 0.3 background events are expected. With more data, we expect to lead the study of neutrino oscillation.

In order to pursue the study of properties of neutrino beyond T2K, we have started the design of next generation water Cherenkov detector, Hyper-Kamiokande (HK). One of the main goals of HK is the search for CP violation in leptonic sector using accelerator neutrino and anti-neutrino beams. The sensitivity to CP violating phase is studied with full simulation. It is shown that with HK and J-PARC accelerator, CP violation can be observed after five years of experiment for a large part of possible parameter space.

In order to reduce the uncertainty in the neutrino oscillation measurements, we have been analyzing data from SciBooNE, an experiment performed at Fermilab to study neutrino-nucleus interaction. We have measured the cross section of the inclusive ν_μ charged current interaction on carbon. Using this measurement, we have also searched for neutrino oscillation together with MiniBooNE collaboration.

We have been developing hybrid photodetector (HPD) combining a large-format phototube technology and avalanche diode as photo-electron multiplier. This year, we have developed 8-inch HPD with all glass design, together with a compact high voltage supply and readout electronics. This device can be deployed for large water Cherenkov detectors, envisioned as the next generation proton-decay/neutrino detectors.

1. H. Fujimori, H. Aihara, S. Mineo, H. Miyatake, S. Miyazaki, H. Nakaya, T. Uchida, "Back-End Readout Electronics for Hyper Suprime-Cam," IEEE Nuclear Science Symposium Conference Record, N14-9, 2010.

2. Y. Nakajima *et al.* [SciBooNE Collaboration], "Measurement of inclusive charged current interactions on carbon in a few-GeV neutrino beam," Phys. Rev. D **83**, 012005 (2011).

3. T.Abe, H. Aihara, M. Iwasaki, K. Kasimura, S. Mineo, T. Uchida, M. Tanaka, Y. Kawai, H. Kyushima, M. Suyama, M. Shiozawa "R&D status of large aperture Hybrid Avalanche Photo-Detector," Nucl.Instrum.Meth.A623:279-281,2010.

8 Asai group

Research Subjects: (1) Particle Physics with the energy frontier accelerators (LEP and LHC) (2) Physics analysis in the ATLAS experiment at the LHC: (Higgs, SUSY and Extra-dimension) (3) Particles Physics without accelerator: tabletop size (4) Positronium and QED

Member: S.Asai

- (1) LHC (Large Hadron Collider) has the excellent physics potential. Our group is contributing to the ATLAS group in the Physics analyses: focusing especially on three major topics, the Higgs boson, Supersymmetry and Extra-dimension.
  - Higgs: We are focusing on Higgs boson whose masses is lighter than 140 GeV. $H \to \gamma\gamma$, $\tau\tau$ and WW are the promising channels. We search for the Higgs with these three modes and No evidence was observed. We need more luminosity for Higgs hunting and we can reach the luminosity of discovery within 2 years.

- SUSY: We contributes SUSY study at the ATLAS experiment as a convener. We have developed methods of the data-driven background estimation for all channels, and we found out that we can estimate background number//distributions from the data itself with accuracy of 10-30% even in the early of the state. Now we have real data and search for the SUSY with the various event topologies, and no evidence was observed in all topologies. We set stringent limit on the dark matter.
- Extra-dimension If the extra-dimension is compactified at a few TeV scale, Mini-black hole and KK excitation are interesting signals. We search for these topologies and we have set the limit of about 2TeV for the planck scale.

- (2) Small tabletop experiments have the good physics potential to discover the physics beyond the standard model, if the accuracy of the measurement or the sensitivity of the research is high enough. We perform the following tabletop experiments:
  - Search for extra-dimension with positronium → invisible.
  - Search for CP violation of the lepton sector using positronium.
  - Precise measurement Search HFS of the positronium.
  - Developing high power (>500W) stable sub THz RF source
  - Spin-rotation of positronium

9 Aoki Group

Subject: Theoretical condensed-matter physics

Members: Hideo Aoki, Takashi Oka

Our main interests are many-body effects in electron systems, i.e., **superconductivity, magnetism and topological systems**, for which we envisage a **materials design for correlated electron systems** and novel **non-equilibrium** phenomena should be realised. Studies in the 2010 academic year include:

- Superconductivity
  - — Superconductivity in iron-based compounds
  - — Superconductivity in solids of aromatic molecules
  - — High-Tc cuprate revisited and anologues designed[1]
  - — Collective modes in multi-band superconductors [2]
- Magnetism
  - — Design of ferromagnetism in cold atoms [3] and organics [4]
  - — Multiferroic multiband systems
- Topological systems: Quantum Hall systems[12] and graphene
  - — Graphene QHE and chiral symmetry[5,6]
  - — Optica (THz) Hall effect in graphene[7]
  - — Many-body and quantum-dot states in graphene [8]
- Non-equilibrium and nonlinear phenomena in correlated electron systems
  - — Non-linear transport in the dielectrically broken Mott insulator [9,10]
  - — Dynamical repulsion-attraction conversion in intense ac fields [11]
  - — Photovoltaic Hall effect in graphene

[1] H. Sakakibara, H. Usui, K. Kuroki, R. Arita and H. Aoki: Two orbital model explains why the single-layer Hg cuprate have higher superconducting transition temperature than the La cuprate, *Phys. Rev. Lett.* **105**, 057003 (2010).

[2] Y. Ota, M. Machida, T. Koyama and H. Aoki: Leggett's collective modes in multiband superfluids and superconductors — Multiple dynamical classes, *Phys. Rev. B* **83**, 060507(R) (2011).

[3] M. Okumura, S. Yamada, M. Machida and H. Aoki: Phase-separated ferromagnetism in spin-imbalanced Fermi atoms loaded on an optical ladder, *Phys. Rev. A* **83**, 031606(R) (2011).

[4] Y. Suwa, R. Arita, K. Kuroki and H. Aoki: First-principles study of ferromagnetism for an organic polymer dimethylaminopyrrole, *Phys. Rev. B* **82**, 235127 (2010).

[5] T. Kawarabayashi, Y. Hatsugai, T. Morimoto and H. Aoki: Generalized chiral symmetry and stability of zero modes for tilted Dirac cones, *Phys. Rev. B* **83**, 153414 (2011).

[6] H. Watanabe, Y. Hatsugai and H. Aoki: Half-integer contributions to the quantum Hall conductivity from single Dirac cones, *Phys. Rev. B* **82**, 241403(R) (2010).

[7] Y. Ikebe, T. Morimoto, R. Masutomi, T. Okamoto, H. Aoki and R. Shimano: Optical Hall effect in the integer quantum Hall regime, *Phys. Rev. Lett.* **104**, 256802 (2010).

[8] P. A. Maksym, M. Roy, M. F. Craciun, S. Russo, M. Yamamoto, S. Tarucha and H. Aoki: Proposal for a magnetic field induced graphene dot, *J. Phys.: Conf. Ser.* **245**, 012030 (2010).

[9] T. Oka and H. Aoki: Dielectric breakdown in a Mott Insulator: many-body Schwinger-Landau-Zener mechanism studied with a generalized Bethe ansatz, *Phys. Rev. B* **81**, 033103 (2010).

[10] M. Eckstein, T. Oka and P. Werner: Dielectric breakdown of Mott insulators in dynamical mean-field theory *Phys. Rev. Lett.* **105**, 146404 (2010).

[11] N. Tsuji, T. Oka, P. Werner and H. Aoki: Changing the interaction of lattice fermions dynamically from repulsive to attractive in ac fields, *Phys. Rev. Lett.*, to be published.

[12] Hideo Aoki: Integer quantum Hall effect (a chapter in *Comprehensive Semiconductor Science & Technology* ed by P. Bhattacharya, R. Fornari and H. Kamimura, Elsevier, 2011).

10 Miyashita Group

Research Subjects: Statistical Mechanics, Phase Transitions, Quantum Spin systems, Quantum Dynamics, Non-equilibrium Phenomena

Member: Seiji Miyashita and Keiji Saito

1. Cooperative Phenomena and Phase Transition

Study on phase transitions and critical phenomena is one of main subjects of the statistical mechanics. We have studied various types of ordering phenomena in systems with large fluctuation. In the last year, we studied the following aspects of phase transitions. [1]

One is the phase transition in long-range Interacting systems. So far, phase transitions of spin systems have been studied mainly on the fixed lattice. However, we pointed out that difference of local lattice structure, e.g. the sizes of the high-spin (HS) and the low-spin (LS) in the spin-crossover materials causes lattice distortions. This degree of freedom of lattice deformation causes an effective long range interaction for ordering of bistable states. We have pointed out that the critical property of this type of models belongs to the universality class of the mean-field model, and also that its dynamical critical properties, such as the spinodal phenomena, are described by the corresponding mean-field theory. In the last year, in particular, we studied on the spatial ordering patterns of the system with long range interaction. In the long range interaction system with periodic boundary condition, the system does not show compact ordering cluster even at the critical point in contrast to the usual short range systems in which the correlation length diverges and infinite clusters appear. [41, 45] We studied how the correlation length changes if both short and long range interactions exists. We derived a scaling relation of the correlation length as function of the ratio of the short and long range interactions, and confirmed by a Monte Carlo simulation. We also studied how switching between the two ordered state occurs in system with open boundary condition, and found a scale-invariant property. [3, 4, 41, 45]

We also studied in which condition systems with long range interaction are described by the mean-field theory. It is known that in the cases where the interaction energy per spin diverges, where the extensivity is not satisfied and the so-called Kac procedure is necessary, the thermal properties are described by the mean-field theory if the order parameter is not conserved. We investigate the condition in detail, and confirmed this property. Moreover, we found that even in this case, the properties in a fixed value of order parameter cannot be described by the mean-filed theory in some parameter region. This indicates that the uniform configuration for the state of mean-field state becomes unstable inn such parameter region. We are studying the properties of such states. [5, 31, 39]

Hiroko Tokoro made experimental studies on novel magnetic materials in collaboration with Ohkoshi laboratory (chemistry department). [6, 58, 59]

We also studies the general structure of the so-called mixed phase which has been found in the generalized 6-state clock model with a quasi-degenerate energy structure. We found various new type phases and phase transitions. [37, 43] We also studied on the classification of the first order phase transitions in the Potts model with the so-called transparent states.

2. Quantum Statistical Mechanics

Cooperative phenomena in quantum systems are also important subject in our group. In quantum systems, they show interesting non-classical behavior. We have studied quantum phase transitions in spin systems and also itinerant electron systems. In particular, the mechanism of Nagaoka ferromagnetism provides an interesting magnetic property in system where we control the chemical potential of the itinerant electrons (Hubbard model). We proposed a system in which the transition between magnetic and non-magnetic state takes place with this mechanism and the property of the model is studied by the DMRG method. [50]

As a study on the exact solvable models, we studied the exact property of spin chain by making use of algebraic Bethe anzatz. In particular, we investigated properties of boundary states of $S = 1$ spin chain. [22, 23, 26, 27, 28, 29] We also studied a nontrivial symmetry in a one-dimensional $S = 1$ bilinear-biquadratic model by an exact diagonalization method. [57].

We also studied the dynamical properties and also response. Coherent dynamics of quantum systems has also various characteristic features, and attracts interests from the view point of quantum information processing. We have studied such novel quantum phases and quantum responses. [2] Parts of the subject are studied as an activity of the JST CREST project (Quantum-mechanical cooperative phenomena and their applications). [47]

Quantum response to external fields is one of the important subjects in our group, and we have studied resonant spectrum of interacting system by proposing a direct numerical method for the Kubo formula, and extended it to systems with dissipative dynamics.[48, 49]。 In the last year, we studied the line spectrum of a spin chain with an alternative Dzyaloshinsky-Moriya interactions at high temperature limit, and analyzed it in the relation with the autocorrelation function of the spin torque which shows a deviation from the gaussian relaxation at long time. We discussed an extension of the Kubo-Tomita theory. [7]

We also studied hybridization of a spin system in the cavity and the cavity photon which attracts interests from the view point of coupling of photon information and materials. We published a paper with the related experiments[8], which has been reviwed as a possible realization of the Quantum RAM. We extended the study to detailed structure of the line shape by studying the energy structure of hybridized systems.

Moreover, we studied origins of decoherence of the Rabi oscillation which is regarded as an evidence of quantum coherence. We classified the characterization of the origins of the decoherence, e.g. the local distribution of magnetic field and the magnetic anisotropy, and the dipolar-dipolar interactions among the spins, etc. We are applying it to the related experiments.

How the equilibrium (canonical distribution) is realized is also a big topic in statistical mechanics. We have study an isolated spin system and study the dynamics explicitly, and observed how the local system approaches to a stationary state and it is resemble to the canonical distribution as a function of strength and type of the interaction between the local system and the rest system. [9]

We have studied quantum effect in the conveyance process of particle dragged by a potential well. We studied origins of the non-adiabatic transition during the process, and analyzed them from the view points of the resonant state for systems with the quantum tunneling.[56]。

We also studied dynamical properties of quantum systems under transverse field in the context of the quantum annealing. [10, 11]。

On the duality between particle and wave in quantum mechanics, we studied in what condition we can realize the wave nature in a model of particles. [12, 13]

As to the transport phenomena, we studied universal feature of the current fluctuation. We derived a generated cumulant function and examine the proposal of the additivity principle of Derrida. We also studied the AC conductance of the heat conductivity. [14, 15, 16, 17, 18, 19, 20, 52, 53, 54, 55]

11 Ogata Group

Research Subjects: Condensed Matter Theory

Member: Masao Ogata, Hiroyasu Matsuura

We are studying condensed matter physics and many body problems, such as strongly correlated electron systems, high-T_c superconductivity, Mott metal-insulator transition, magnetic systems, low-dimensional electron systems, mesoscopic systems, organic conductors, unconventional superconductivity, and Tomonaga-Luttinger liquid theory. The followings are the current topics in our group.

- High-T_c superconductivity
  Inhomogeneity and two-gap features in high-T_c superconductors.
  Mott metal-insulator transition and superconductivity.[6]
- New superconductor: Iron-pnictide
  Effects of nonmagnetic impurities in iron-pnictide superconductors.[1]
  Quasi-particle interference patterns in d-wave superconductors.
  Orbital-selective superconductivity and the effect of lattice distortion.[5]
- Organic conductors
  Modeling and magnetism in one-dimensional Fe-phthalocyanine compounds.
  Novel spin-liquid states in an anisotropic-triangular spin-system.
  Static nonequilibrium state of the competing charge orders under an electric field.
- Theories of anisotropic superconductivity
  Spatial patterns of the two-dimensional FFLO superconductivity near zero temperature.
- Dirac electrons
  Dissipationless current due to the interband effects of magnetic field in Dirac fermion systems.
  Spin-polarized currents in Dirac fermion systems.
- Four-state classical Potts model with a novel type of frustrations
- Theories on heavy fermion systems
  A renormalization-group study for the two-level Kondo model with conduction electrons.[2]
  Competition between the Kondo-Yoshida singlet and the crystal-field singlet for f^2 configuration.[3]
  Crossover from local Fermi liquid to heavy Fermi liquid.[4]

[1] T. Kariyado and M. Ogata: J. Phys. Soc. Jpn. **79**, 083704 (2010).

[2] H. Matsuura, S. Tanikawa, and K. Miyake: J. Phys. Soc. Jpn. **79**, 074705 (2010).

[3] S. Nishiyama, H. Matsuura, and K. Miyake: J. Phys. Soc. Jpn. **79**, 104711 (2010).

[4] H. Watanabe and M. Ogata: Phys. Rev. B **81**, 113111 (2010).

[5] N. Arakawa and M. Ogata: to appear in J. Phys. Soc. Jpn.. "Orbital-Selective Superconductivity and the Effect of Lattice Distortion in Iron-Based Superconductors"

[6] H. Yokoyama, T. Miyagawa, M. Ogata: submitted to J. Phys. Soc. Jpn.. "Effect of Doublon-Holon Binding on Mott transition—Variational Monte Carlo Study of Two-Dimensional Bose Hubbard Models"

12 Tsuneyuki Group

Research Subjects: Theoretical Condensed-matter physics

Member: Shinji Tsuneyuki and Yoshihiro Gohda

Computer simulations from first principles enable us to investigate properties and behavior of materials beyond the limitation of experiments, or rather to predict them before experiments. Our main subject is to develop and apply such techniques of computational physics to investigate basic problems in condensed matter physics, especially focusing on prediction of material properties under extreme conditions like ultra-high pressure or at surfaces where experimental data are limited. Our principal tool is molecular dynamics (MD) and first-principles electronic structure calculation based on the density functional theory (DFT), while we are also developing new methods that go beoynd the limitation of classical MD and DFT.

In FY2010, we predicted theoretically novel two-dimensional interface ferromagnetism at AlN/MgB_2(0001) using DFT calculations (Y. Gohda and S. Tsuneyuki, Phys. Rev. Lett. **106**, 047201 (2011)). First-principles electron transport calculations demonstrate that this interfacial spin polarization is responsible for quantum spin transport. The magnetization can be controlled by applied gate bias voltages.

We also developed or improved several methodologies for first-principles study of electronic, structural and dynamical properties of materials. One of the major achievements is that we obtained first converged results of the electronic structure calculation of a large-gap insulator by the Transcorrelated (TC) method, a wave funtion theory we have developed for several years.

In summary, our research subjects in FY2010 were as follows:

- New methods of electronic structure calculation
  - Generalized anharmonic lattice model of crystals for investigating thermal conductivity
  - First-principles wavefunction theory for solids based on the Transcorrelated method
  - FMO-LCMO method: a new method of electronic structure calculation of huge biomolecules based on the fragment molecular orbital (FMO) method
- Applications of first-principles electronic structure calculation
  - Two-Dimensional Intrinsic Ferromagnetism at Nitride-Boride Interfaces
  - Oxygen vacancy and hydrogen impurities in $BaTiO_3$
  - Electric dipole layer at the water-electrode interface

13 Fujimori Group

Research Subjects: Photoemission Spectroscopy of Strongly Correlated Systems

Member: Atsushi Fujimori and Teppei Yoshida

We study the electronic structure of strongly correlated systems using high-energy spectroscopic techniques such as angle-resolved photoemission spectroscopy and soft x-ray magnetic circular dichroism using synchrotron radiation. We investigate mechanisms of high-temperature superconductivity [1], metal-insulator transitions, giant magnetoresistance, carrier-induced ferromagentism, spin/charge/orbital ordering in strongly correalted systems such as transition-metal oxides [2], magnetic semiconductors [3], and their interfaces.

[1] S. Ideta, K. Takashima, M. Hashimoto, T. Yoshida, A. Fujimori, H. Anzai, T. Fujita, Y. Nakashima, A. Ino, M. Arita, H. Namatame, M. Taniguchi, K. Ono, M. Kubota, D. H. Lu, Z.-X. Shen, K. M. Kojima, and S. Uchida: Enhanced superconducting gaps in the tri-layer high-temperature $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ cuprate superconductor, Phys. Rev. Lett. **104** 227001–1-4, (2010).

[2] T. Yoshida, M. Hashimoto, T. Takizawa, A. Fujimori, M. Kubota, K. Ono, and H. Eisaki: Mass renormalization in the band width-controlled Mott-Hubbard systems $SrVO_3$ and $CaVO_3$ studied by angle-resolved photoemission spectroscopy, Phys. Rev. B **82**, 085119–1-5 (2010).

[3] V.R. Singh, Y. Sakamoto, T. Kataoka, M. Kobayashi, Y. Yamazaki, A. Fujimori, F.-H. Chang, D.-J. Huang, H.-J. Lin, C.T. Chen, H. Toyosaki, T. Fukumura, and M. Kawasaki: Bulk and surface magnetization of Co atoms in rutile $Ti_{1-x}Co_xO_{2-\delta}$ thin films revealed by x-ray magnetic circular dichroism, J. Phys. Condens. Mat. **23**, 176001–1-5 (2011).

14 Uchida Group

Research Subjects: High-T_c superconductivity

Member:Uchida Shin-ichi (professor), Kakeshita Teruhisa. (research associate)

1. Project and Research Goal

The striking features of low-dimensional electronic systems with strong correlations are the "fractionalization" of an electron and the "self-organization" of electrons to form nanoscale orders. In one dimension (1D), an electron is fractionalized into two separate quantum-mechanical particles, one containing its charge (holon) and the other its spin (spinon). In two dimensions (2D) strongly correlated electrons tend to form spin/charge stripe order.

Our study focuses on 1D and 2D copper oxides with various configurations of the corner-sharing CuO_4 squares. The common characteristics of such configurations are the quenching of the orbital degree of freedom due to degraded crystal symmetry and the extremely large exchange interaction (J) between neighboring Cu spins due to large $d-p$ overlap (arising from 180° Cu-O-Cu bonds) as well as to the small charge-transfer energy. The quenching of orbitals tends to make the holon and spinon to be well-defined excitations in 1D with quantum-mechanical character, and the extremely large J is one of the factors that give rise to superconductivity with unprecedentedly high Tc as well as the charge/spin stripe order in 2D cuprates. The experimental researches of our laboratory are based upon successful synthesis of high quality single crystals of cuprate materials with well-controlled doping concentrations which surpasses any laboratory/institute in the world. This enables us to make systematic and quantitative study of the charge/spin dynamics by the transport and optical measurements on the strongly anisotropic systems. We also perform quite effective and highly productive collaboration with world-leading research groups in the synchrotron-radiation, μSR and neutron facilities, and STM/STS to reveal electronic structure/phenomena of cuprates in real- and momentum-space.

2. Accomplishment

(1) Ladder Cuprate

Significant progress has been made in the experimental study of a hole-doped two-leg ladder system $Sr_{14-x}Ca_xCu_{24}O_{41}$ and undoped $La_6Ca_8Cu_{24}O_{41}$:

1) From the high pressure (P) study we constructed and x-P phase diagram (in collaboration with Prof. N. Môri's group). We find that the superconductivity appears as a superconductor-insulator transition only under pressures higher than 3GPa and that the superconducting phase is restricted in the range of x larger than 10. In lower P and smaller x regions the system is insulating.

2) The pairing wave function in the superconducting phase has an s-wave like symmetry which is evidenced by a coherence peak at T_c in the nuclear relaxation rate, revealed by the first successful NMR measurement under high pressure.

3) The origin of the insulating phase dominating the whole $x-P$ phase diagram is most likely the charge order of doped holes or hole pairs as suggested by the presence of a collective charge mode in the x=0, $Sr_{14}Cu_{24}O_{41}$, compound in the inelastic light scattering (with G. Blumberg, Bell Lab.), microwave and nonlinear conductivity (with A. Maeda and H. Kitano, U. of Tokyo), and inelastic X-ray scattering (with P. Abbamonte and G. A. Sawatzky).

4) In the undoped compound $La_6Ca_8Cu_{24}O_{41}$ spin thermal conductivity is remarkably enhanced to the level of silver metal along the ladder-leg direction due to the presence of a spin gap and to a ballistic-like heat transport characteristic of 1D.

(2) Observation of Two Gaps, Pseudogap and Superconducting Gap, in Underdoped High-T_c Cuprates.

The most important and mysterious feature which distinguishes cuprate from conventional superconductors is the existence of " pseudogap " in the normal state which has the same d-wave symmetry as the superconducting gap does. We employed c-axis optical spectrum of $Yba_2Cu_3O_{6.8}$ as a suitable probe for exploring gaps with d-wave symmetry to investigate the inter-relationship between two gaps. We find that the two gaps are distinct in energy scale and they coexist in the superconducting state, suggesting that the pseudogap is not merely a gap associated with pairs without phase coherence, but it might originate from a new state of matter which competed with d-wave superconductivity.

(3) Nanoscale Electronic Phenomena in the High-T_c Superconducting State

The STM/STS collaboration with J. C. Davis' group in Cornell Univ. is discovering numerous unexpected nanoscale phenomena, spatial modulation of the electronic state (local density of states, LDOS), in the superconducting CuO_2 planes using STM with sub-Å resolution and unprecedentedly high stability. These include (a) "+" or "×" shaped quasiparticle (QP) clouds around an individual non-magnetic Zn (magnetic Ni) impurity atom, (b) spatial variation (distribution) of the SC gap magnitude, (c) a "checkerboard" pattern of QP states with four unit cell periodicity around vortex cores, and (d) quantum interference of the QP. This year's highlights are as follows:

1) Granular structure of high-Tc superconductivity

The STM observation of "gap map" has been extended to various doping levels of $Bi_2Sr_2CaCu_2O_{8+\delta}$. The result reveals an apparent segregation of the electronic structure into SC domains of ∼3mm size with local energy gap smaller than 60meV, located in an electronically distinct background ("pseudogap" phase) with local gap larger than 60meV but without phase coherence of pairs. With decrease of doped hole density, the (coverage) fraction of the superconducting area decreases or the density of the number of superconducting islands decreases. Apparently, this is related to the doping dependence of superfluid density as well as the doping dependence of the normal-state carrier density.

2) Homogeneous nodal superconductivity and heterogeneous antinodal states

Modulation of LDOS is observed even without vortices, at zero magnetic field. In this case, the modulation is weak and incommensurate with lattice period, showing energy (bias voltage) dependence. The dispersion is explained by quasiparticle interference due to elastic scattering between characteristic regions of momentum-space, consistent with the Fermi surface and the d-wave SC gap determined by ARPES (angle-resolved-photoemission).

These dispersive quasiparticle interference is observed at all dopings, and hence the low-energy states, dominated by the states on the " Fermi arc " formed surrounding the gap nodes, are spatially homogeneous(nodal superconductivity). By contrast, the quasiparticle states near the antinodal region degrade in coherence with decreasing doping, but have dominant contribution to superfluid density. This suggests that the volume fraction of spatial regions all of whose Fermi surface contributes to superfluid decreases with reduced doping. The result indicates the special relationship between real-space and momentum-space electronic structure.

15 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Toru HIRAHARA

Surfaces of materials are platforms of our research where rich physics is expected due to the low-dimensionality and symmetry break down. (1) electronic/spin/mass transports, (2) atomic/electronic structures, (3) phase transitions, (4) electronic excitations, (5) spin states and magnetism, and (6) epitaxial growths of coherent atomic/molecular layers/wires on semiconductor surfaces, topological surfaces, and nano-scale phases such as surface superstructures and ultra-thin films. We use ultrahigh vacuum experimental techniques such as electron diffraction, scanning electron microscopy, scanning tunneling microscopy/spectroscopy (STM/S), photoemission spectroscopy, *in-situ* four-point-probe conductivity measurements with four-tip STM and monolithic micro-four-point probes, and surface mageto-optical Kerr effect measurements. Main results in this year are as follows.

(1) Surface electronic transport: Current-induced spin polarization effect in strong spin-orbit-interaction materials. Control of surface electronic states and their conductivity of topological insulators. Anisotropic transport on a quasi-one-dimensional metallic surface.

(2) Surface phases, ultra-thin films, and phase transitions: Order-disorder phase transition, charge-density-wave transition, Mott transition on various metal-induced surface superstructures of Si. Quantum-well state in ultra-thin metal films. Rashba effect in surface state and hybridization with quantum-well states in thin films.

(3) Surface magnetism: Monolayer ferromagnetic surfaces. Diluted magnetic surface states.

(4) Construction of new apparatuses: Green's-function STM (low-temperature four-tip STM), micro-four-point probes apparatus at mK under strong magnetic field.

[1] S. Yamazaki, Y. Hosomura, I. Matsuda, R. Hobara, T. Eguchi, Y. Hasegawa, and S. Hasegawa: *Metallic Transport in a Monatomic Layer of In on a Silicon Surface*, Physical Review Letters **106**, 116802 (Mar, 2011).

[2] N. Miyata, R. Hobara, H. Narita, T. Hirahara, S. Hasegawa, and I. Matsuda: *Development of surface magneto-transport measurement with micro-four-point probe method and the measurement of Bi nanofilm on Si(111)*, Japanese Journal of Applied Physics **50**, 036602 (Mar, 2011).

[3] I. Matsuda, K. Kubo, F. Nakamura, T. Hirahara, S. Yamazaki, W. H. Choi, H. W. Yeom, H. Narita, Y. Fukaya, M. Hashimoto, A. Kawasuso, S. Hasegawa, and K. Kobayashi: *Electron compound nature in a surface atomic layer of two-dimensional triangle lattice*, Physical Review B **82**, 165330 (Nov, 2010).

[4] T. Hirahara, Y. Sakamoto, Y. Takeichi, H. Miyazaki, S. Kimura, I. Matsuda, A. Kakizaki, and S. Hasegawa: *Anomalous transport in an n-type topological insulator ultrathin Bi_2Se_3 film*, Physical Review B **82**, 155309 (Oct. 2010) (selected as Editors 担 uggestions).

[5] H. Morikawa, K. S. Kim, Y. Kitaoka, T. Hirahara, S. Hasegawa and H. W. Yeom: *Conductance transition and interwire ordering of Pb nanowires on Si(557)*, Physical Review B **82**, 045423 (Jul, 2010).

[6] A. Nishide, Y. Takeichi, T. Okuda, A. A. Taskin, T. Hirahara, K. Nakatsuji, F. Komori, A. Kakizaki, Y. Ando, and I. Matsuda: *Spin-polarized surface bands of a three-dimensional topological insulator studied by high-resolution spin- and angle-resolved photoemission spectroscopy*, New Journal of Physics **12**, 065011 (Jun, 2010).

[7] Y. Niinuma, Y. Saisyu, T. Hirahara, R. Hobara, S. Hasegawa, H. Mizuno, and T. Nagamura: *Development of an UHV-SMOKE system using permanent magnets*, e-Journal of Surface Science and Nanotechnology **8**, 298(Jun, 2010).

[8] T. Hirahara, Y. Sakamoto, Y. Saisyu, H. Miyazaki, S. Kimura, T. Okuda, I. Matsuda, S. Murakami, and S. Hasegawa: *Ttopological metal at the surface of an ultrathin $Bi_{1-x}Sb_x$ alloy film*, Physical Review B **81**, 165422 (Apr, 2010)(selected as Editors' Suggestions).

[9] Y. Sakamoto, T. Hirahara, H. Miyazaki, S. Kimura, and S. Hasegawa: *Spectroscopic evidence of a topological quantum phase transition in ultrathin Bi_2Se_3 films*, Physical Review B **81**, 165432 (Apr, 2010).

[10] K. He, Y. Takeichi, M. Ogawa, T. Okuda, P. Moras, D. Topwal, A. Harasawa, T. Hirahara, C. Carbone, A. Kakizaki, and I. Matsuda: *Direct spectroscopic evidence of spin-dependent hybridization between Rashba-split surface states and quantum-well states*, Physical Review Letters **104**, 156805 (Apr, 2010).

16 Group

Research Subjects: Low Temperature Physics (Experimental):
Quantum fluids and solids with strong correlations and frustration,
Scanning tunneling microscopy and spectroscopy of two dimensional electron systems and superconductors.

Member: Hiroshi Fukuyama, Tomohiro Matsui

Our current interests are (i) quantum phases with strong correlations and frustration in two dimensional (2D) helium three (^{3}He), (ii) novel phenomena related to Graphene, monatomic sheet of carbon atoms. We are investigating these phenomena at ultra-low temperatures down to 50 μK, using various experimental techniques such as NMR, calorimetry, scanning tunneling microscopy and spectroscopy (STM/STS), low energy electron diffraction (LEED) and transport measurement, *etc.*

1. **Ground-state of two dimensional ^{3}He:**

   It is an interesting open question to ask whether the critical point, i.e., the gas-liquid transition, exists in strictly 2D ^{3}He. The previous quantum many-body calculations predict interestingly that ^{3}He has the critical point but ^{4}He does not in pure 2D case. We have measured low-temperature heat capacities (C) of the second-, third- and fourth-layer ^{3}He adsorbed on a graphite surface preplated with monolayer ^{4}He to elucidate if the ground state of each layer is gas or liquid phase. The elucidation is based on the fact that the coefficient (γ) of T-linear term in $C_{(T)}$ in degenerated fermion system is determined by the surface area over which the fermions spread and the quasi-particle effective mass. It had been found until last year that there is the critical point over third layer and ^{3}He atoms form 2D paddles at low densities ($\rho < 1.5$ nm^{-2}). This year, we found that even the second layer, where the confinement potential from the substrate is stronger, does not have the critical point, too. Moreover, the density of the 2D paddle is comparable with that in third layer. Therefore, we can conclude that the ground state of 2D ^{3}He is the liquid phase, and that the interaction between ^{3}He atoms in 2D is attractive in average.

2. **Other ongoing experiments on 2D ^{3}He:**

   We are preparing a new sample cell for high-precision heat capacity measurements of the possible order-disorder transition near $T = 1$ K in the second layer ^{3}He on graphite using a ZYX exfoliated graphite substrate which has much larger micro-crystalline size than the previous one. The purpose of this experiment is to confirm the existence of such a commensurate phase, the 4/7 phase, at the expected density around which many interesting quantum phenomena are proposed to emerge at low temperatures. Designing of a LEED (low energy electron diffraction) experiment below 0.5 K is also undergoing in order to determine the structures of the commensurate phase unambiguously. A cryogen-free dilution refrigerator which will be used for these next generation experiments has been tested successfully with the lowest temperature of 12 mK and the cooling power of 200 μW at $T = 100$ mK.

3. **Kosterlitz-Thouless transition of the Sn island network on Graphene:**

   Since graphene is fabricated on top of a substrate, one can directly couple dopants with two dimensional electron gas in graphene, whose carrier density and type can be tuned by an applied gate voltage. Thus, graphene could provide an ideal substrate for study of proximity effect. Actually, graphene has been shown to effectively carry proximity-induced Josephson currents injected from contacting electrodes. On the other hand, it has also known that elemental superconductor Sn readily form self-assembled islands when deposited on graphene at room temperature. Therefore, Sn islands on graphene is a good candidate to study the superconducting proximity effect and 2D Josephson junction network.

   The graphene samples are prepared by exfoliating Kish graphite onto SiO_2 substrate. Sn is deposited on graphene with photo-lithographed electrodes in high vacuum, and their transport properties are measured at temperatures down to 0.5 K and in magnetic fields up to 9 T. A sample with Sn of nominally 30 nm thick actually shows islands with about 300 nm diameter and about 20 nm separation in scanning electron microscope image. The temperature dependence of the resistance shows two types of superconducting transitions. The resistance drops suddenly with decreasing temperature at $T \sim 3.9$ K reflecting the superconducting transition of Sn islands. At 2.0 K $< T <$ 3.9 K, the resistance shows $\exp(-1/\sqrt{T})$ dependence suggesting Kosterlitz-Thouless (KT) superconducting transition in 2D. From this analysis, KT transition temperature T_{KT} is estimated to be 2.06 K. The resistance does not become zero and gradually decreases with decreasing temperature at $T <$ 2.0 K, that is presumably because of the finite size effect, since there estimated to be only 6 islands in between electrodes. In magnetic fields of $B > B_c = 77$ mT, the slope of the temperature dependence changes its sign from metallic to insulating. In addition, the resistance shows thermally activated $1/T$ dependence in $B < B_c$. These results suggest the field induced superconductor-insulator transition in this superconducting Sn network on graphene.

4. **Band gap tuning in functionalized Graphene:**

   Graphene has a gapless band structure, and it is importand for graphene electronics to engineer a band gap in this material. Since the gapless character in graphene is protected by the high symmetry of its lattice, in which two carbon sites in the unit cell are equivalent, the simplest way of gap-opening is to lift the symmetry. One of the approaches to modify the electronic properties is to functionalize the graphene by atom deposition. It is expected that there would be a energy gap with enhanced density of states (DOS) when adatoms form ordered structure on graphene. To experimentaly confirm this property, we preliminary studied the DOS of Xe atom adsorbed on graphite with STS. We found that a energy gap with an order of ±1 V is created when the Xe form a $\sqrt{3} \times \sqrt{3}$ adsorbed structure.

17 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

We study low temperature electronic properties of semiconductor two-dimensional systems.
The current topics are following:

1. Two dimensional electrons at cleaved semiconductor surfaces:
   At the surfaces of InAs and InSb, conduction electrons can be induced by submonolayer deposition of other materials. Recently, we have performed in-plane magnetotransport measurements on in-situ cleaved surfaces of p-type substrates and observed the quantum Hall effect which demonstrates the perfect two dimensionality of the inversion layers. Research on the hybrid system of 2D electrons and adsorbed atoms has great future potential because of the variety of the adsorbates as well as the application of scanning probe microscopy techniques.

   In 2010, we have modified our experimental setup in order to mount a scanning tunneling microscope.

2. Superconductivity of ultrathin Bi films on cleaved GaAs surfaces:
   We have performed magnetotransport measurements on ultrathin Bi films on GaAs(110) surfaces. To reduce disorder arising from the substrate, we used cleaved surfaces of insulating GaAs. The critical film thickness for superconductivity was obtained to be 0.42 nm, which is thinner than the previous data for different kinds of substrates. In the study of $I - V$ characteristics, we observed discontinuous jump in the temperature dependence of the power α in $V \propto I^{\alpha}$, which is associated with "universal jump" of the Kosterlitz-Thouless transition. This indicates that the KT transition can occur in amorphous films as well as Josephson-coupled arrays.

3. Strongly correlated two dimensional systems:
   Cyclotron resonance of two-dimensional electrons is studied at low temperatures down to 0.4 K for a high-mobility Si/SiGe quantum well which exhibits a metallic temperature dependence of dc resistivity ρ. The relaxation time $\tau_{\rm CR}$ shows a negative temperature dependence, which is similar to that of the transport scattering time τ_t obtained from ρ. The ratio $\tau_{\rm CR}/\tau_t$ at 0.4 K increases as the electron density N_s decreases, and exceeds unity when N_s approaches the critical density for the metal-insulator transition. [R. Masutomi *et al.*, Phys. Rev. Lett. (accepted for publication).]

18 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Shinichi Watanabe

We study light-matter interactions and many body quantum correlations in solids. In order to investigate the role of electron and/or spin correlations in the excited states as well as the ground states, we focus on the low energy electromagnetic responses, in particular in the terahertz(THz) (1THz∼4meV) frequency range where quasi-particle excitations and various collective excitations exist. The research summary in this year is as follows.

1. **High density electron-hole system:** We investigated the thermodynamics of high density electron and hole(e-h) system in Si by optical pump and terahertz probe experiments. Through the observation of 1s-2p transition of excitons at 3 THz, we revealed the cooling dynamics of the e-h system and also the formation dynamics of excitons. Towards the realization of quantum degenerate phases such as exciton Bose Einstein condensation and e-h BCS phase, an essential difficulty exists in indirect gap semiconductors, i.e., the spontaneous condensation of e-h system into e-h droplets(EHD). To overcome this difficulty, we developed a pressure anvil cell that can apply uniaxial stress to the crystal so that the formation of EHD is suppressed. We also studied the fine structures of excitons in Si under the magnetic field. Zeeman and diamagnetic shift of excitons are clearly observed through the1s-2p exciton transitions. By applying the magnetic field, accumulation of excitons into the spin- forbidden lowest energy state is observed.

2. **Optical Hall effect:** We investigated the optical(terahertz frequency) Hall effect in: 1) 2-dimensional electron gas(2DEG) system of a GaAs/AlGaAs heterostructure in the integer quantum Hall regime, and 2) itinerant ferromagnet $SrRuO_3$, by using highly sensitive THz polarization spectroscopy technique. In the 2DEG system, the optical Hall conductivity $\sigma_{xy}(\omega)$ exhibits a plateau-like behavior around the Landau-level filling $\nu = 2$, indicating that the carrier localization effect, a crucial ingredient in the integer QHE, affects the optical Hall conductivity even in the THz regime. In a $SrRuO_3$ film, we studied the THz frequency anomalous Hall effect(AHE) and determined $\sigma_{xy}(\omega)$ from the Faraday rotation spectrum. A resonant structure was observed in $\sigma_{xy}(\omega)$ spectrum, which is reasonably accounted for by the Berry phase theory of AHE.

3. **Study of electromagnon in multiferroics:** Electric active magnetic excitation, termed electromagnon, has been proposed in multiferroic $TbMnO_3$ as a collective excitation in a ferroelectric spin-spiral phase, but their origin had been controversial. We performed comprehensive study of electromagnon in rare earth manganite $RMnO_3$(R=Dy, Tb, EuY) by THz time-domain spectroscopy and experimentally clarified two types of electromagnon, arising from 1) symmetric($s_i \cdot s_j$) and 2) anti-symmetric($s_i \times s_j$) exchange interaction between the neighboring Mn spins.

4. **Development of intense THz light source:** We developed an intense THz light source with the peak electric-field amplitude as large as 0.9 MV/cm, by using optical rectification of femtosecond laser pulses in a $LiNbO_3$ crystal. By using the developed intense THz pulses, we have demonstrated; 1) dynamical Stark effect of excitons in carbon nanotubes, 2) THz field-acceleration of carriers in carbon nanotubes that results in impact excitation of excitons, 3) THz pulse-induced melting of charge-order in a quasi-2D organic conductor $\theta-(\text{BEDT-TTF})_2\text{CsZn(SCN)}_4$.

References

[1] T. Suzuki and R. Shimano,Phys. Rev. B **83**, 085207 (2011).

[2] R. Shimano, T. Suzuki, Physica Status Solidi (c) **8**, p. 1153-1156 (2011).

[3] S. Watanabe, N. Minami, and R. Shimano, Optics Express **19**, 1528 (2011).

[4] J. Fujioka, Y. Ida, Y. Takahashi, N. Kida, R. Shimano, and Y. Tokura,Phys. Rev. B **82**, 140409(R) (2010).

[5] S. Seki, N. Kida, S. Kumakura, R. Shimano, and Y. Tokura, Phys. Rev. Lett. **105**, 097207 (2010).

[6] T. Ogawa, S. Watanabe, N. Minami, and R. Shimano,Appl. Phys. Lett. **97**, 041111 (2010).

[7] Y. Ikebe, T. Morimoto, R. Masutomi, T. Okamoto, H. Aoki, and R. Shimano,Phys. Rev. Lett. **104**, 256802 (2010).

[8] S. Watanabe, R. Kondo, S. Kagoshima, and R. Shimano, Physica B **405**, S360-S362 (2010).

19 Theoretical Astrophysics Group

Research Subjects: Oservational Cosmology, Extrasolar Planets,

Member: Yasushi Suto, & Atsushi Taruya

The Theoretical Astrophysics Group carries out a wide range of research programmes. However, astrophysics is a very broad field of research, and it goes without saying that our group alone cannot cover all the various important astrophysical research topics on hand. Among others we place emphasis on the "Observational Cosmology".

"Observational Cosmology" attempts to understand the evolution of the universe on the basis of the observational data in various wavebands. The proper interpretation of the recent and future data provided by COBE, ASCA, the Hubble telescope, SUBARU, and large-scale galaxy survey projects is quite important both in improving our understanding of the present universe and in determining several basic parameters of the universe which are crucial in predicting the evolutionary behavior of the universe in the past and in the future. Our current interests include nonlinear gravitational evolution of cosmological fluctuations, formation and evolution of proto-galaxies and proto-clusters, X-ray luminosity and temperature functions of clusters of galaxies, hydrodynamical simulations of galaxies and the origin of the Hubble sequence, thermal history of the universe and reionization, prediction of anisotropies in the cosmic microwave background radiation, statistical description of the evolution of mass functions of gravitationally bound objects, and statistics of gravitationally lensed quasars.

Let us summarize this report by presenting recent titles of the doctor and master theses in our group;

2010

- Precise measurement of number-count distribution function of SDSS galaxies

2009

- The Central Engine of Gamma-Ray Bursts and Core-Collapse Supernovae Probed with Neutrino and Gravitational Wave Emissions
- Numerical Studies on Galaxy Clustering for Upcoming Wide and Deep Surveys: Baryon Acoustic Oscillations and Primordial Non-Gaussianity
- Toward a precise measurement of neutrino mass through nonlinear galaxy power spectrum based on perturbation theory
- Toward Remote Sensing of Extrasolar Earth-like Planets
- Improved Modeling of the Rossiter-McLaughlin Effect for Transiting Exoplanetary Systems
- Forecasting constraints on cosmological parameters with CMB-galaxy lensing cross-correlations

2008

- Holographic non-local operators
- Neutrino Probes of Core-collapse Supernova Interiors
- Inhomogeneity in Intracluster Medium and Its Cosmological Implications
- Nuclear "pasta" structure in supernovae
- Investigation of the Sources of Ultra-high-energy Cosmic Rays with Numerical Simulations
- Formation of Pulsar Planet Systems -Comparison with the Standard Scenario of Planetary Formation-

2007

- The Rossiter effect of extrasolar transiting planetrary systems ? perturbative approach and application to the detection of planetary rings
- Stability of flux compactifications and de Sitter thermodynamics
- Study of core-collapse supernovae in special relativistic magnetohydrodynamics
- Spectroscopic Studies of Transiting Planetary Systems
- The relation of the Galactic extinction map to the surface number density of galaxies

- Brane Inflation in String Theory 2006
- Numerical studies on cosmological perturbations in braneworld
- Inflationary braneworld probed with primordial black holes
- Galaxy Biasing and Higher-Order Statistics
- Probing circular polarization of Gravitational Wave Background with Cosmic Microwave Background Anisotropy
- Gravitational Collapse of Population III Stars

2005

- Brane gravity and dynamical stability in warped flux compactification
- Neutrino Probes of Galactic and Cosmological Supernovae
- Detectability of cosmic dark baryons through high-resolution spectroscopy in soft X-ray band
- Propagation of Ultra-High Energy Cosmic Rays in Cosmic Magnetic Fields
- The study of nuclear pasta investigated by Quantum Molecular Dynamics

2004

- Strong Gravitational Lenses in a Cold Dark Matter Universe
- Effect of Rotation and Magnetic Field on the Explosion Mechanism and Gravitational Wave in Core-Collapse Supernovae
- ” Bulk Fields in Braneworld ”
- “ Gravitational collapse and gravitational wave in the brane-world ”
- Magnetohydrodynamical Simulation of Core-Collapse Supernovae
- A Search for the Atmospheric Absorption in the Transiting Extrasolar Planet HD209458b with Subaru HDS
- Baryogenesis and Inhomogeneous Big Bang Nucleosynthesis
- The large-scale structure of SDSS quasars and its cosmological implication

2003

- Non-Gravitational Heating of Galaxy Clusters in a Hierarchical Universe
- Discoveries of Gravitationally Lensed Quasars from the Sloan Digital Sky Survey
- One, Two, Three ? measuring evolved large scale structure of the Universe
- Higher-order Statistics as a probe of Non-Gaussianity in Large Scale Structure
- Primordial black holes as an imprint of the brane Universe
- Probing the Extra Dimensions with Gravitational Wave Background of Cosmological Origin

20 Murao Group

Research Subjects: Quantum Information Theory

Member: Mio Murao, Peter Turner

Quantum information processing seeks to perform tasks which are impossible or not effective with the use of conventional classical information, by using quantum information described by quantum mechanical states. Quantum computation, quantum cryptography, and quantum communication have been proposed and this new field of quantum information processing has developed rapidly especially over the last 15 years. Entanglement is nonlocal correlation that appears in certain types of quantum states (non-separable states) and has become considered as a fundamental resource for quantum information processing. In our group, we investigate new properties of multipartite and multi-level entanglement and the use of these properties as resources for quantum information processing. Our current projects are the following:

- Distributed quantum information processing
  - Quantifying "Globalness" of unitary operations on quantum information [1,2,3]
  - Error models for distributed quantum information processing
  - Distributed Quantum Computation over the Buttery Network [4]
  - Controllization of a unitary operation
  - Functionality-preserving randomization for unitary operations
- Entanglement theory
  - Multipartite entanglement [5]
  - Random states generation by Hamiltonian dynamics with multi-body interactions
  - Entanglement property of states randomly distributed in a Hilbert space with symmetry
  - Entanglement witness non-equilibrium steady state [6]
  - Detecting entanglement production during a non-equilibrium process
  - Structural characteriziation of graph states for quantum information processing [7]
- Quantum tomography
  - Error probability analysis in quantum tomography [8]
  - Quantum tomography under incomplete settings
  - Adaptive quantum estimation
  - Operational indistinguishability in quantum tomography [9]
  - Continuous variable 2-designs
- Foundation of quantum mechanics
  - Memory effect of the environment and thermalization of a quantum system
  - Analysis of bipartite nonlocal correlation and non-locality distillation

Please refer our webpage: http://www.eve.phys.s.u-tokyo.ac.jp/indexe.htm

References

1. A. Soeda and M. Murao, *Delocalization power of global unitary operations on quantum information"*, *New J. Phys.* **12***, 093013 (2010)*

2. A. Soeda and M. Murao, *Comparing globalness of bipartite unitary operations acting on quantum information: delocalization power, entanglement cost, and entangling power*, arXiv:1010.4599 (2010)

3. A. Soeda, P. S. Turner and M. Murao, *Entanglement cost of implementing controlled-unitary operations*, arXiv:1008.1129 (2010)

4. A. Soeda, Y. Kinjo, P.S. Turner and M. Murao, *Quantum Computation over the Butterfly Network*, arXiv:1010.4350 (2010)

5. M. Aulbach, D. Markham and M. Murao, *The maximally entangled symmetric state in terms of the geometric measure*, New J. Phys. **12**, 073025 (2010)

6. J. Hide, *A steady state entanglement witness*, arXiv:1102.0220 (2010)

7. M. Mhalla, M. Murao, S. Perdrix, M. Someya and P. S. Turner, *Which graph states are useful for quantum information processing?*, arXiv: 1006.2616 (2010)

8. T. Sugiyama, P. S. Turner, and M. Murao, *Error probability analysis in quantum tomography: A tool for evaluating experiments*, Phys. Rev A **83**, 012105 (2011)

9. P. S. Turner, T. Sugiyama, T. Rudolph, *Testing for multiparticle indistinguishability*, Proceedings of the 10th International Conference on Quantum Communication, Measurement & Computing, (2010)

21 Ueda Group

Research Subjects: Bose-Einstein condensation, Fermionic superfluidity, cold molecules, mesurement theory, quantum information, quantum control

Member: Masahito Ueda and Yuki Kawaguchi

21.1 Quantum States of Ultracold Atoms

Bogoliubov theory and Lee-Huang-Yang corrections in spin-1 and spin-2 Bose-Einstein condensates in the presence of the quadratic Zeeman effect

We develop Bogoliubov theory of spin-1 and spin-2 Bose-Einstein condensates (BECs) in the presence of a quadratic Zeeman effect, and derive the Lee-Huang-Yang (LHY) corrections to the ground-state energy, pressure, sound velocity, and quantum depletion. We investigate all the phases of spin-1 and spin-2 BECs that can be realized experimentally.We also examine the stability of each phase against quantum fluctuations and the quadratic Zeeman effect. Furthermore, we discuss a relationship between the number of symmetry generators that are spontaneously broken and that of Nambu-Goldstone (NG) modes. It is found that in the spin-2 nematic phase there are special Bogoliubov modes that have gapless linear dispersion relations but do not belong to the NG modes.

Quasi-Nambu-Goldstone Modes in Bose-Einstein Condensates

We show that quasi-Nambu-Goldstone (NG) modes, which play prominent roles in high energy physics but have been elusive experimentally, can be realized with atomic Bose-Einstein condensates. The quasi-NG modes emerge when the symmetry of a ground state is larger than that of the Hamiltonian. When they appear, the conventional vacuum manifold should be enlarged. Consequently, topological defects that are stable within the conventional vacuum manifold become unstable and decay by emitting the quasi-NG modes. Contrary to conventional wisdom, however, we show that the topological defects are stabilized by quantum fluctuations that make the quasi-NG modes massive, thereby suppressing their emission.

Spontaneous magnetic ordering in a ferromagnetic spinor dipolar Bose-Einstein condensate

We study the spin dynamics of a spin-1 ferromagnetic Bose-Einstein condensate with magnetic dipole-dipole interaction (MDDI) based on the Gross-Pitaevskii and Bogoliubov theories. We find that various magnetic structures such as checkerboards and stripes emerge in the course of the dynamics due to the combined effects of spin-exchange interaction, MDDI, quadratic Zeeman and finite-size effects, and nonstationary initial conditions. However, the short-range magnetic order observed by the Berkeley group [Phys. Rev. Lett. 100, 170403 (2008)] is not fully reproduced in our calculations; the periodicity of the order differs by a factor of 3 and the checkerboard pattern eventually dissolves in the course of time.

Hydrodynamic equation of a spinor dipolar Bose-Einstein condensate

We introduce equations of motion for spin dynamics in a ferromagnetic Bose-Einstein condensate with magnetic dipole-dipole interaction, written using a vector expressing the superfluid velocity and a complex scalar describing the magnetization. This simple hydrodynamical description extracts the dynamics of spin wave and affords a straightforward approach by which to investigate the spin dynamics of the condensate. To demonstrate the advantages of the description, we illustrate dynamical instability and magnetic fluctuation preference, which are expressed in analytical forms.

Nonuniversal Efimov Atom-Dimer Resonances in a Three-Component Mixture of ^{6}Li

The Efimov states are universal trimer states in a three-body system with resonant two-body interactions. We measured the magnetic-field dependence of the atom-dimer loss a three-component mixture of ^{6}Li atoms, and observed two enhanced atom-dimer loss at 602 G and 685 G. These loss peaks correspond to the degeneracy points of the energy levels of dimers and the Efimov stetaes, and the number of peaks indicates the existence of the ground and first excited Efimov trimers. We also found that the locations of these peaks disagree with universal theory predictions, in a way that cannot be explained by non-universal 2-body properties. We constructed theoretical models that characterize the non-universal three-body physics of three-component ^{6}Li atoms with a monotonic-energy-dependent three-body parameter. This result was published in Physical Review Letters in 2010.

21.2 Quantum Information, Quantum Measurement, and Information thermodynamics

Experimental realization of the Szilard engine [Nature Physics 6, 988-992 (2010)]

In 1929, Leo Szilard proposed a model of "Maxwell's demon," which converts the obtained information to the free energy (or the work) by feedback control. We have demonstrated the experimental realization of the Szilard engine for the first time. We performed a real-time feedback control on a single colloidal particle of the submicron scale at the room temperature. As a result, we succeeded to increase the particle 褰冱 free energy by the feedback control, and observed that the free-energy increase was larger than the input work. We have also experimentally verified the generalized Jarzynski equality, which was theoretically proposed by us. This work was the collaboration with the Muneyuki group (Chuo Univ.) and the Sano group (Univ. Tokyo), was published in Nature Physics, and was highlighted by News and Views.

Theoretical analysis of the quantum Szilard engine [Phys. Rev. Lett. 106, 070401 (2011)]

We theoretically studied the quantum version of the Szilard engine with multi particles. As a result, we derived the general formula that gives the work that can be extracted from the engine. In particular, we found the quantum effect for the case of the single quantum particle, in which we need a positive amount of work to insert a barrier to the engine. We also found that the identical-particle effect is observed for the multi particle case. For example, the amount of work that can be extracted from the Bosonic engine is larger than the work from the Fermionic engine. The quantum work was shown to converge to the classical work with distinguishable particles. This work was published in Physical Review Letters, selected for Editor's suggestion, and featured by Physics Viewpoint.

22 Makishima Group & Nakazawa Group

Research Subjects: High Energy Astrophysics with Energetic Photons using Scientific Satellites, Development of Cosmic X-Ray/γ-Ray Instruments

Member: Kazuo Makishima, Kazuhiro Nakazawa

Using space-borne instruments such as *Suzaku* and *MAXI*, we study cosmic high-energy phenomena in the X-ray and γ-ray frequencies. We have been deeply involved in the development of the Hard X-ray Detector (HXD) onboard *Suzaku*, and are developing new instruments for future satellite missions.

Mass Accreting Black Holes: Mass accretion onto black holes provides a very efficient way of X-ray production. Confirmed black holes have masses in the range from several to several billion solar masses. Utilizing wide-band *Suzaku* spectra, we have shown that the matter accreting onto stellar-mass black holes and active galactic nuclei [3] both forms inhomogeneous hot "corona" that Comptonizes soft photons into hard X-rays. Evidence for rapid black-hole rotation, claimed by some foreign researchers, is considered rather inconclusive or doubtful [5].

Neutron Stars with Various Magnetic Fields: Using *Suzaku*, we are studying neutron stars with a variety of magnetic field strengths, B. The least magnetized ones with $B < 10^9$ G, known as X-ray burst sources, behave rather similarly to stellar-mass black holes. Ordinary binary X-ray pulsars have $B \sim 10^{12}$ G, as estimated via the detection of electron cyclotron absorption lines. Some "fast transient" objects may have $B \sim 10^{13}$ G. Finally, we have revealed that about 10 "magnetars", supposed to have $B = 10^{14-15}$ G, emit unusual hard X-ray components, extending to ~ 100 keV with very flat spectra [2]. We speculate that the magnetism of neutron stars is a manifestation of ferromagnetism in nuclear matter.

Plasma Heating and Particle Acceleration: The universe is full of processes of plasma heating and particle acceleration. In fact, the most dominant known component of cosmic baryons exists in the form of X-ray emitting hot ($\sim 10^8$ K) plasmas associated with clusters of galaxies. There, large-scale magnetic structures, and their interactions with moving galaxies, are considered to be of essential importance [4].

White Dwarfs and the Galactic Ridge Emission: From the 1980', an apparently extended X-ray emission, called Galactic Ridge X-ray Emission, was known to distribute along our Galactic plane. Using *Suzaku*, we have shown that this phenomenon can be considered, at least in energies above ~ 10 keV, as an assembly of X-ray emission from numerous mass-accreting magnetic white dwarfs. This is supported by a close resemblance between the Galactic Ridge X-ray Emission spectra and those of nearby individual white dwarf binaries [1].

Future Instrumentation: In collaboration with many domestic and foreign groups, we are developing a successor to *Suzaku*, *ASTRO-H*. Scheduled for launch in 2014, it will conduct hard X-ray imaging observations, high-resolution X-ray spectroscopy, and low-energy gamma-ray observations. We contribute to the development of two onboard instruments, the Hard X-ray Imager and the Soft Gamma-ray Detectors. Our effort includes the development of "SpaceWire" technology, large BGO scintillators, and mechanical/thermal designs of the instruments.

1. Yuasa, T., Nakazawa, K., Makishima, K., Saitou, K., Ishida, M., Ebisawa, K., Mori, H. & Yamada, S.: "White Dwarf Masses in Intermediate Polars Observed with the *Suzaku* Satellite", *Astron. Astrophys.* **520**, A25 (2010)
2. Enoto, T., Nakazawa, K., Makishima, K., Rea, N., Hurley, K. & Shibata, S.: "Broadband Study with *Suzaku* of the Magnetar Class", *The Astrophysical Journal Letters*, **722**, Issue 2, L162–167 (2010)
3. Noda, H., Makishima, K., Uehara, Y., Yamada, S., Nakazawa, K.: "Suzaku Discovery of a Hard Component Varying Independently of the Power-Law Emission in MCG6-30-15 *Publ. Astr. Soc. Japan* **63**, in press (2011)
4. Takahashi, I., Kawaharada, M., Makishima, K., Matsushita, K., Fukazawa, Y., Ikebe, Y., Kitaguchi, T., Kokubun, M., Nakazawa, K., Okuyama, S., Ota, N. & Tamura, T. "X-ray Diagnostics of Thermal Conditions of the Hot Plasmas in the Centaurus Cluster", *Astrophys. J.* **701**, 377–395 (2009)

5. Yamada, S., Makishima, K., Uehara, Y., Nakazawa, K., Takahashi, H., Dotani, T., Ueda, Y., Ebisawa, K., Kubota, A. & Gandhi, P.: "Is the Black Hole in GX 339-4 Really Spinning Rapidly?", *Astrophys. J. Let.* **707**, L109–L103 (2009)

23 Takase Group

Research Subjects: High Temperature Plasma Physics Experiments, Spherical Tokamak, Wave Heating and Current Drive, Nonlinear Physics, Collective Phenomena, Fluctuations and Transport, Advanced Plasma Diagnostics Development

Member: Yuichi Takase, Akira Ejiri, Yoshihiko Nagashima

Thermonuclear fusion, the process that powers the sun and stars, is a promising candidate for generating abundant, safe, and clean power. In order to produce sufficient fusion reactions, isotopes of hydrogen, in the form of hot and dense plasma, must be confined for a long enough time. A magnetic configuration called the tokamak has reached the level where the International Thermonuclear Experimental Reactor (ITER) is being constructed to study the behavior of burning plasmas. However, improvement of the cost-effectiveness of the fusion reactor is still necessary. The spherical tokamak (ST) offers a promising approach to increasing the efficiency by raising the plasma beta (the ratio of plasma pressure to magnetic pressure). High beta plasma research using ST is a rapidly developing field worldwide, and is being carried out in our group using the TST-2 spherical tokamak. TST-2 is now located in a new experimental building in Kashiwa Campus. Our group is tackling the problem of creating and sustaining ST plasmas using radio frequency (RF) waves.

In TST-2 RF power is used to form the initial ST plasma and to ramp up the plasma current $I_{\rm p}$. Previous experiments have demonstrated plasma start-up using RF powers at 2.45 GHz (ECH) and/or 21 MHz. RF waves at 200 MHz were excited with either symmetric or asymmetric wavenumber spectrum (standing wave or travelling wave). With 200 MHz RF power, the lower limit of magnetic field strength for plasma start-up could be extended downward by roughly a factor of three compared to ECH. $I_{\rm p}$ ramp-up to 12 kA was achieved with the travelling wavenumber spectrum in combination with a slowly increasing vertical field, compared to typical levels of 1–2 kA achievable with the symmetric spectrum. When the wave-driven current is in the same direction as $I_{\rm p}$, a stable ST configuration is obtained, but when the wave-driven current is in the opposite direction a large $I_{\rm p}$ modulation (transition between two states) was observed. The asymmetric behavior observed with travelling waves launched in opposite directions indicates that the contribution of wave-driven current is significant. A build-up of energetic electrons as $I_{\rm p}$ is ramped up, observed by hard X-ray spectroscopy, also indicates the importance of the wave-driven current. The plasma configuration was reconstructed based on magnetic measurements. Two representative equilibria were obtained, one with centrally peaked current density profile, and the other with a peak near the outboard boundary. With ECH, both types are observed depending on the gas pressure. Only the outboard peaked current density profile was obtained by RF with symmetric spectrum, whereas centrally peaked current density profile was also obtained by RF with travelling spectrum. These profiles are probably manifestations of the different RF power deposition profiles. RF power (200 MHz) was also excited in inductively formed plasmas with $I_{\rm p} \simeq 100$ kA. No conclusive evidence of current drive or heating has been observed with up to 130 kW of RF power. This is most likely due to the low magnetic field (0.1 T) used in this experiment. For the toroidal mode number (18) of the excited wave and the plasma density ($10^{18}\,{\rm m}^{-3}$) measured near the antenna, higher magnetic fields (0.3 T) are needed for the excited wave to reach the plasma core, based on numerical modelling of RF waves. Experiments at higher magnetic fields with improved antennas which can excite a more desirable wave polarization are planned in 2011.

Plasma transport is governed by microscopic turbulence. In order to measure the electron temperature fluctuation using electrostatic probes, the fast voltage sweeping technique was developed. The validity of the current-voltage characteristic curve was confirmed. The fitting errors in the evaluation of the electron temperature itself are less than 10 % of fluctuation levels in the electron temperature. In order to improve the signal-to-noise ratio in low density plasmas, and to measure the electron pressure anisotropy and the electron current density, a multi-pass Thomson scattering system is being developed. As a proof-of-principle, a double-pass Thomson scattering system is being tested. The electron pressure parallel to the magnetic field ($p_{\rm e\parallel}$), electron pressure perpendicular to the magnetic field ($p_{\rm e\perp}$), and electron current density

(j_e) at magnetic axis can be measured. This system should be able to measure temperature anisotropies of over 15 % ($T_{e\parallel}/T_{e\perp} > 15\%$) in high density ($n_e > 3 \times 10^{18}$ m^{-3}) plasmas. A high time resolution electron temperature and density measurement using helium line intensity ratios based on the collisional-radiative model is being developted. The intensity ratio can be calculated using Collisional-Radiative model. A 24-channel system (8 spatial channels at three wavelengths) is in use. Initial results indicate that both electron temperature and density have profiles peaked on the outboard side.

24 Tsubono Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Kimio TSUBONO and Yoich ASO

The detection of gravitational waves is expected to open a new window into the universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars; these information can not be obtained by other means such as optics, radio-waves or X-ray. Worldwide efforts are being continued in order to construct detectors with sufficient sensitivity to catch possible gravitational waves.

In 2010, a new science project, LCGT (Large-scale Cryogenic Gravitational wave Telescope)was approved and funded by the Leading-edge Research Infrastructure Program of the Japanese government. This underground telescope is expected to catch gravitational waves from the coalescence of neutron-star binaries at the distance of 200Mpc.

A space laser interferometer, DECIGO, was proposed through the study of the gravitational wave sources with cosmological origin. DECIGO could detect primordial gravitational waves from the early Universe at the inflation era.

We summarize the subjects being studied in our group.

- Ground based laser interferometric gravitational wave detectors
  - LCGT has started !
  - Design of LCGT interferometer
- Space laser interferometer
  - Space laser interferometer, DECIGO, DECIGO pathfinder, DPF
  - FP cavity for DPF
  - DPF gradiometer in space
  - Study of the effect of the residual gas
  - SWIM$_{\mu\nu}$
- Development of a gravitational wave detector using magnetic levitation
  - Data analysis for the background gravitational waves
  - Generation of the mimic data for gravitational wave analysis
- High sensitive laser interferometer using non-classical light
  - Generation of the squeezed light
- Development of the ultra stable laser source
  - Laser stabilization using a cryogenic cavity
  - Study of the cavity support
  - Study of the cryostat design
- Gravitational force at small distances

- Measurement using torsion-type resonant antenna
- Measurement by the spectroscopy of the molecule

references

[1] Masaki Ando, Koji Ishidoshiro, Kazuhiro Yamamoto, Kent Yagi, Wataru Kokuyama, Kimio Tsubono, and Akiteru Takamori: Torsion-Bar Antenna for Low-Frequency Gravitational-Wave Observations, Phys. Rev. Lett. **105** (2010) 161101.

[2] Seiji Kawamura, Masaki Ando, Naoki Seto, Shuichi Sato, Takashi Nakamura, Kimio Tsubono *et al.*, and the DECIGO working group: The Japanese space gravitational wave antenna: DECIGO, Class. Quantum Grav. 28 (2011) 094011.

25 Sano Harada Group

Research Subjects: Physics of out-of-equilibrium systems and living matter

Members: Masaki Sano and Takahiro Harada

Main research topics of our group are nonlinear dynamics, pattern formation in dissipative systems, nonequilibrium statistical mechanics, and biophysics. By closely studying oscillations, chaos, and turbulent behavior and fluctuations in fluidic, solidic, and granular materials as well as chemical reactions and biological systems, we wish to discover a diverse of novel phenomena and distils simple and universal laws underlying such phenomena. Our research are grounded on dynamical systems theory, statistical mechanics, soft matter physics, and laboratory experiments. The following are the representative research subjects in our laboratory.

1. Study of turbulence

(1) Search for the ultimate scaling regime in developed thermal turbulence

(2) Study of statistical properties and coherent structures in turbulence

(3) Turbulence - turbulence transition in electro hydrodynamic convection of liquid crystals

2. Nonlinear Dynamics and Chaos

(1) Pattern forming phenomena and their universalities in dissipative systems including granular materials

(2) Spatio-temporal dynamics in spatially extended dissipative systems

3. Nonequilibrium statistical mechanics and softmatter physics

(1) Fundamental studies on the nature of fluctuations and responses of system far from equilibrium

(2) Developing a general theory of measurements on small complex systems

(3) Manipulation of soft materials via novel optical trap techniques

(4) Softmatter physics on polymers, thermophoretic flows and other related topics

3. Dynamical aspects of biological systems

(1) Single molecule level measurement of DNA collapsing, DNA-protein interaction, and gene expression

(2) Study of slow dynamics in cellular functions

(3) Mechanical aspects of cell migration

(4) Pattern formation of bacteria

References

1. Kazumasa A. Takeuchi and Masaki Sano: Universal Fluctuations of Growing Interfaces: Evidence in Turbulent Liquid Crystals, Physical Review Letters, **104**, 230601 (2010).
2. Toru Hiraiwa, Miki Y. Matsuo, Takahiro Ohkuma, Takao Ohta, and Masaki Sano: Dynamics of a deformable self-propelled domain, Europhys. Lett. **91**, 20001 (2010).
3. Shoichi Toyabe, Takahiro Sagawa, Masahito Ueda, Eiro Muneyuki, and Masaki Sano: Experimental demonstration of information-to-energy conversion and validation of the generalized Jarzynski equality, Nature Physics, **6**, 988 (2010).
4. Hong-Ren Jiang, Natsuhiko Yoshinaga, Masaki Sano: Active Motion of Janus Particle by Self-thermophoresis in Defocused Laser Beam, Phys. Rev. Lett. **105**, 268302 (2010). (selected for an Editor's Suggestion and highlighted with a Viewpoint in Physics of APS.)
5. Helene Delanoe-Ayari, Jean-Paul Rieu, and Masaki Sano: 4D Traction Force Microscopy Reveals Asymmetric Cortical Forces in Migrating Dictyostelium Cells, Phys. Rev. Lett., **105**, 248103 (2010).
6. Takahiro Harada, Hisa-Aki Tanaka, Michael J. Hankins, and Istvan Z. Kiss: Optimal Waveform for the Entrainment of a Weakly Forced Oscillator, Phys. Rev. Lett. **105**, 088301 (2010).
7. Makito Miyazaki and Takahiro Harada: Bayesian estimation of the internal structure of proteins from single-molecule measurements, J. Chem. Phys., **134**, 085108 (2011).
8. Makito Miyazaki and Takahiro Harada: Go-and-Back method: Effective estimation of the hidden motion of proteins from single-molecule time series, J. Chem. Phys., **134**, 135104 (2011).
9. Kyogo Kawaguchi and Masaki Sano: Efficiency of Free Energy Transduction in Autonomous Systems, arXiv:1103.1961.
10. Marguerite Bienia and Masaki Sano: Non-destructive ultrasonic velocimetry for central region velocity fields in turbulent Rayleigh-Benard convection of mercury, Flow Measurement and Instrumentation, DOI 10.1016/j.flowmeasinst.2011.03.009, online publication, Mar-24 (2011).

26 Yamamoto Group

Research Subjects: Submillimeter-wave and Terahertz Astronomy, Star and Planet Formation, Chemical Evolution of Interstellar Molecular Clouds, Development of Terahertz Detectors

Member: Satoshi Yamamoto and Nami Sakai

Molecular clouds are birthplaces of new stars and planetary systems, which are being studied extensively as an important target of astronomy and astrophysics. Although the main constituent of molecular clouds is a hydrogen molecule, various atoms and molecules also exist as minor components. The chemical composition of these minor species reflects formation and evolution of molecular clouds as well as star formation processes. It therefore tells us how each star has been formed. We are studying star formation processes from such a astrochemical viewpoint.

Since the temperature of a molecular cloud is as low as 10 K, an only way to explore its physical structure and chemical composition is to observe the radio wave emitted from atoms, molecules, and dust particles. In particular, there exist a number of atomic and molecular lines in the millimeter to terahertz region, and we are observing them with various large radio telescopes in the world.

We are conducting a line survey of low-mass star forming regions with Nobeyama 45 m telescope and ASTE 10 m telescope, aiming at detailed understanding of chemical evolution from protostellar disks to protoplanetary disks. In the course of this effort, we have recently established a new chemistry occurring in the vicinity of a newly born star, which is called Warm Carbon Chain Chemistry (WCCC). In WCCC, carbon-chain molecules are produced by gas phase reactions of CH_4 which is evaporated from ice mantles. This has recently been confirmed by our detection of CH_3D in one of the WCCC sources, L1527. Existence of WCCC clearly indicates a chemical diversity of low-mass star forming regions, which would probably reflect a variety of star formation. We are now studying how such chemical diversity is brought into the protoplanetary disks.

In parallel to such observational studies, we are developing a hot electron bolometer mixer (HEB mixer) for the future terahertz astronomy. We are fabricating the phonon cooled HEB mixer using NbTiN and NbN in our laboratory. Our NbTiN mixer shows the noise temperature of 570 K at 1.5 THz, which is the best performance at this frequency in spite of the use of the wave-guide mount. Furthermore, we successfully realized the waveguide-type NbN HEB mixer by using the NbN/AlN film deposited on the quartz wafer. The 0.8/1.5 THz dual-band HEB mixer receiver is now being assembled, which will be installed on the ASTE 10 m telescope for astronomical observations in 2011.

[1] Sakai, N., Sakai, T., Hirota, T., and Yamamoto, S., Abundant Carbon-Chain Molecules toward the Low-Mass Protostar IRAS04368+2557 in L1527?h, ApJ, 672, 371 (2008).

[2] Sakai, N., Sakai, T., Hirota, T., and Yamamoto, S., Deuterated Molecules in Warm Carbon Chain Chemistry: The L1527 Case?h, ApJ, 702, 1025 (2009).

[3] Shiino, T., Shiba, S., Sakai, N., Yamakura, T., Jiang, L., Uzawa, Y., Maezawa, H., and Yamamoto, S., Improvement of the Critical Temperature of Superconducting NbTiN and NbN Thin Films Using the AlN Buffer Layer?h, Supercond. Sci. Technol. 23, 045004 (2010).

27 Sakai (Hirofumi) Group

Research Subjects: Experimental studies of atomic, molecular, and optical physics

Member: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between a strong nonresonant laser field and induced dipole moments of the molecules. (2) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation). (3) Ultrafast phenomena in atoms and molecules in the attosecond time scale. (4) Controlling quantum processes in atoms and molecules using shaped ultrafast laser fields. A part of our recent research activities is as follows:

(1) All-optical molecular orientation [1]

We report clear evidence of all-optical orientation of carbonyl sulfide molecules with an intense nonresonant two-color laser field in the adiabatic regime. The technique relies on the combined effects of anisotropic hyperpolarizability interaction and anisotropic polarizability interaction and does not rely on the permanent dipole interaction with an electrostatic field. It is demonstrated that the molecular orientation can be controlled simply by changing the relative phase between the two wavelength fields. The present technique brings researchers a new steering tool of gaseous molecules and will be quite useful in various fields such as electronic stereodynamics in molecules and ultrafast molecular imaging.

(2) Dependence of the generation efficiency of high-order sum and difference frequencies in the extreme ultraviolet region on the wavelength of an added tunable laser field [2]

We investigate the dependence of the generation efficiency of sum and difference frequencies in the extreme ultraviolet (xuv) region on the wavelength of an added tunable laser field. The wavelength of the added field ranges from 600 nm to 1500 nm. The generation efficiency of sum and difference frequencies is dramatically enhanced when the wavelength of the added field is longer than that of the fundamental field for pure harmonics. The discussions are held to the added field with perturbative intensity first, and they are further extended to that with nonpertubative intensity.

(3) Effect of nuclear motion observed in high-order harmonic generation from D_2/H_2 molecules with intense multi-cycle 1300 nm and 800 nm pulses [3]

We investigate high-order harmonic generation from D_2/H_2 molecules with intense multi-cycle pulses centred both at 1300 nm (60 fs) and at 800 nm (50 fs) together with that from N_2/Ar as a reference. The experimental observations with 1300 nm pulses are different from those with 800 nm pulses both in spectral shapes and in intensity ratios I_{D_2}/I_{H_2}. The effect of nuclear motion in D_2 and H_2 is more distinctive for 1300 nm pulses than for 800 nm pulses. With multi-cycle pulses of 50–60 fs, the intensity ratios I_{D_2}/I_{H_2} are found to be higher for both 800 nm and 1300 nm pulses than those with few-cycle pulses of 8 fs, which is attributed partly to the contribution of the coupling between the 1sσ_g and 2pσ_u states in D_2^+ and H_2^+ molecular ions during the higher order returns of the electron wave packets.

[1] Keita Oda, Masafumi Hita, Shinichirou Minemoto, and Hirofumi Sakai, Phys. Rev. Lett. **104**, 213901 (2010).

[2] Yuichiro Oguchi, Shinichirou Minemoto, and Hirofumi Sakai, J. Phys. Soc. Jpn. **80**, 014301 (2011).

[3] Hiroki Mizutani, Shinichirou Minemoto, Yuichiro Oguchi, and Hirofumi Sakai, J. Phys. B: At. Mol. Opt. Phys. **44**, 081002 (2011).

28 Gonokami Group

Research Subjects: Experimental studies on many-body quantum physics by light-matter interaction, Optical phenomena in artificial nanostructures, Development of laser based coherent light source

Member: Makoto Gonokami, Kosuke Yoshioka

Our new research activities have started within the Department of Physics. We are trying to explore new aspects of many-body quantum systems and their exotic quantum optical effects through designed light-matter interactions. Our current target consists of a wide variety of matter, including excitons and electron-hole ensemble in semiconductors, antiferromagnetic magnons and ultracold atomic gases. In particular, we have been investigating the Bose-Einstein condensation phase of excitons, which is considered the ground state of electron-hole ensemble but as yet not proven experimentally. Based on quantitative spectroscopic measurements, the temperature and density are determined for an exciton gas in a quasi-equilibrium condition trapped inside a high purity crystal kept below 1 K.We also investigate novel optical and terahertz-wave responses for some artificial nanostructures obtained by advanced micro-fabrication technologies. As the Director of the Photon Science Center, within the Graduate School of Engineering, a project was started to develop new coherent light sources; covering a broad frequency range from terahertz to soft X-rays. This year, in collaboration with RIKEN, the Foundation for Coherent Photon Science Research was established. This is one of the Advanced Research Foundation initiatives from the Ministry of Education, Culture, Sports, Science and Technology. Within this initiative, we are developing intense and stable coherent light sources at a high repetition rate (That facility is named "Photon Ring").

This year the following activities included:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
    (a) Achievement of Bose-Einstein condensation phase of excitons in semiconductors[1][5]
    (b) Low-temperature, many-body phenomena in electron-hole systems in diamond
    (c) Study strongly-correlated many-body systems using ultra-cold atomic gases
2. The quest for non-trivial optical responses and development of applications:
    (a) Control of circularly polarized spontaneous emission with artificial chiral periodic nanostructures [4]
    (b) Magnetic THz radiation from NiO anitiferromagnetic resonance [3]
    (c) THz radiation from graphite thin films [2]
3. Development of novel coherent light sources and spectroscopic methods
    (a) Mode-locked fiber lasers
    (b) Accumulation of femtosecond laser pulses in passive cavities
    (c) Higher-order photon correlation measurements using a photon-counting streak camera
    (d) Established the Foundation for Coherent Photon Science Research

References

[1] K. Yoshioka, T. Ideguchi, Andre Mysyrowicz, and M. Kuwata-Gonokami: Quantum inelastic collisions between paraexcitons in Cu_2O, Phys. Rev. B **82**, 041201 (2010).

[2] Reported in Nature Photonics **4**, 673 (2010).

[3] T. Higuchi, N. Kanda, H. Tamaru, M. Kuwata-Gonokami: Selection rules for light-induced magnetization of a crystal with threefold symmetry: The case of antiferromagnetic NiO, Phys. Rev. Lett. **106**, 047401 (2011).

[4] K. Konishi, M. Nomura, N. Kumagai, S. Iwamoto, Y. Arakawa, and M. Kuwata-Gonokami: Circularly Polarized Light Emission from Semiconductor Planar Chiral Nanostructures, Phys. Rev. Lett. **106**, 057402 (2011).

[5] K. Yoshioka, E. Chae, and M. Kuwata-Gonokami: Transition to a Bose-Einstein condensate and relaxation explosion of excitons at sub-Kelvin temperatures, Nature Communications to be published.

29 Nose Group

Research Subjects:Molecular Mechanism of Neural Network Formation

Member:Akinao Nose, Hiroshi Kohsaka and Etsuko Takasu

What is the physical basis of formation of the brain? The aim of our laboratory is to elucidate the molecular mechanism of neural development and function by using, as a model, the simple nervous system of the fruitfly, Drosophila. We focus on the synapses between motor neurons and their target muscles, and study the molecular mechanisms of how specific synaptic partners recognize each other and form synaptic connections. The following research plans are in progress.

1. Molecular mechanism of the neuromuscular target recognition

The proper functioning of the nervous system depends on precise interconnections of distinct types of neurons. Therefore, understanding how neurons specifically find and recognize their target cells is a central question in neuroscience. We have identified specific recognition molecules that are expressed in specific target cells and determine synaptic specificity.

1.1. Neural wiring by a negative signal: identification of a repulsive target cue that determines synaptic specificity.

The final matching of pre- and postsynaptic cells is thought to be mediated by specific molecular cues expressed on the target cells. While previous studies demonstrated essential roles of several target-derived attractive cues, less is known about the role of repulsion by non-target cells. In collaboration with Prof. Hiroyuki Aburatani (Research Center of Advanced Science and Technology, University of Tokyo), we conducted single-cell microarray analysis of two neighboring muscles (called M12 and M13) in Drosophila, which are innervated by distinct motor neurons, by directly isolating them from dissected embryos. We identified a number of potential target cues that are differentially expressed between the two muscles, including M13-enriched Wnt4, a secreted protein of the Wnt family. When the function of Wnt4 was inhibited, motor neurons that normally connect with M12 formed smaller synapses on M12 but instead, inappropriately connected with M13. Conversely, forced expression of Wnt4 in M12 inhibited synapse formation by these motor neurons. These results suggest that Wnt4 generates target specificity by preventing synapse formation on a non-target muscle.

2. Live-imaging of synapse formation in vivo

Synapses are specialized junctions through which neurons signal to each other and to other target cells such as muscles and are crucial to the functioning of the nervous system. However, the mechanism of how the synapses form during development remains poorly understood. We applied live imaging of fluorescent fusion proteins expressed in the target cells to visualize the process of synapse formation in developing embryos.

2.1 Bidirectional recognition for neuronal matchmaking

The mechanism of how specific neural connections are formed in living animals is one of the significant topics in neuroscience. A traditional view is one-sided: motile growth cones of the presynaptic neurons actively search for the target cell, whereas the target cells wait still to be selected by adequate partner neurons. We found that not only presynaptic neurons but also postsynaptic target cells actively search for their partners during the formation of neural network. Such bidirectional recognition might be critical for the development of precise neural connections not only in Drosophila but also in other animals including humans.

30 Higuchi Group

Research Subjects: Motor proteins in in vitro, cells and mice

Member: Hideo Higuchi and Motoshi Kaya

We succeeded in measuring stiffness and step size of single-few myosin molecules at in vitro system and imaging the dynamics of GFP-EB1 molecules in mice, that is, in vivo. The detail are as following. Skeletal muscles are necessary not only for body segment movements, but also for our daily communications, such as speaking, writing and facial expressions. Skeletal myosins are an essential protein that interacts with actin filaments and generates forces by stretching the elastic portion of myosin heads during muscle contractions. It has been well known that the mechanical efficiency of muscle contraction can be up to 50 %, which is much higher than that of 15 % in automobile or of 1 % in micro-machines. Theoretically, the contribution of friction to the energy loss is more pronounced as the body size decreases. Thus, our question is why a nano-scale protein, skeletal myosin, can achieve such a high mechanical efficiency? In order to address this question, we measured the elasticity of single myosin molecules and the displacements generated by myosins by the combination of optical trapping and fluorescence imaging techniques with a few nanometer and pico-newton accuracy. We found that myosins become extremely stiff when they are stretched during the force generation period, while they becomes much more complaint when they are compressed after the force generation. In the presence of ATP, myosins generate the sliding movement of actin filament by 8 nm. The biphasic elastic response implies that single skeletal myosins are optimally designed to generate the contractile force efficiently by enhancing the ability of the force generation before the force generation while minimizing the resistance force after the force generation. Microtubles (MTs) are highly dynamic and polar structures that are involved in many important cellular processes including mitosis, migration, adhesion, cargo trafficking, in addition to tumor metastasis. Endbinding protein 1 (EB1) is a MT plus-end binding proteins that are specifically accumulated at the polymerizing end of MTs. In this study, we imaged GFP-EB1 to observed the real-time MT dynamics in living cells and mice. Using a spinning disc confocal microscopy the comet-like localizations of GFP-EB1 were observed in human breast cancer cell line. We analyzed the velocity of GFP-EB1 comets, indicating MT growing speed with the nanometer scale, by tracking the comet centers using an automated computer program. It was faster around centrosome in the central region of the cell than submembrane region. We also imaged successfully GFP-EB1 in three-dimensionally cultured cells in the extracellular matrix that mimics the three-dimensional structure of living tissue. To determine MT dynamics in living mice, breast cancer cells expressed GFP-EB1 were xenografted in nude mice. GFP-EB1 comets were observed under the confocal microscopy in vivo. These techniques have potential to enable quantitative analysis of MT dynamics in living mice, for example, under the presence of anticancer reagents.

[1] Hirota Y., A. Meunier, S.Huang, T. Shimozawa, O.Yamada, Y.S Kida, M. Inoue, T. Ito, H. Kato, M. Sakaguchi, T. Sunabori, M. Nakaya, S. Nonaka, T. Ogura, H. Higuchi, H. Okano, N.Spassky, and *K. Sawamoto. Planar polarity of multiciliated ependymal cells involves the anterior mi-gration of basal bodies regulated by non-muscle myosin II. Development 137, 3037-3046 (2010)

[2] Kaya M. and *H. Higuchi. Non-linear elasticity and an 8 nm working stroke of single myosin molecules in myofilaments. Science 329, 686-689 (2010)

[3] Fujita H, H. Hatakeyama, TM. Watanabe, M. Sato, H. Higuchi and * M. Kanzaki. Identifica-tion of Three Distinct Functional Sites of Insulin-mediated GLUT4 Trafficking in Adipocytes Using Quantitative Single Molecule Imaging. Mol. Biol. Cell 21, 2721-2731 (2010)

[4] Watanabe TM, H. Tokuo, K. Gonda, H. Higuchi and * M. Ikebe. Myosin-X induces filopodia by multiple elongation mechanism. J. Biol. Chem. 285, 19605-14 (2010)